

Modeling Mining Economics and Materials Markets to Inform Criticality Assessment and Mitigation

by

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Abstract

Conventional criticality-assessment methods drawn from the existing literature are often limited to evaluations of scarcity risks, or rely on price as an indicator of criticality. Such approaches, however, are ill-suited to a firm’s material procurement planning. A simulation tool — the **M:5** model — has been developed to model the behavior and dynamics of materials markets. Grounded on economic theory, the model also draws upon the characteristics of mining economics and market imperfections, while offering a flexible structure adaptable to different markets and requiring few inputs. The **M:5** model has been designed to enable manufacturers and policy-makers to compare the outcomes of different scenarios, informing decisions about material purchasing and market regulation.

Model results illustrate common behaviors of materials markets viewed as critical, such as those of Rare Earth Elements and Platinum Group Metals. Analyses illustrate the interaction between demand growth rate and market concentration, as well as the impact of price elasticity of demand on market behaviors. Moreover, an effective recycling stream is shown to be an efficient policy to mitigate price excursions, especially in the presence of disruptive events. A variety of potential private and public mitigating policies are assessed in light of model results, to address common risks encountered in critical materials markets. In addition, this thesis presents how the model can be used to actually develop and compare such policies.

While the initial purposes of the model — namely, enabling scenario comparisons and gaining qualitative insights on specific materials markets — has been fulfilled in this work, future developments on the model could include the endogenous treatment of recycling and adding price-responsiveness to the handling of stock, so as to refine its correspondence to actual markets’ behaviors.

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Chapter 1

Introduction

One of the most important challenges facing any manufacturer is the need to carefully plan for the procurement of the necessary materials, matching the resources on hand with anticipated demand in a timely manner while limiting inventory or undersupply costs. This planning task not only requires a careful estimation of the type and quantity of materials required to meet demand, but also the assurance of a reliable and cost-effective source of supply for the planning horizon.

While the physical availability of materials plays a large role in production planning, other factors ought to be taken into account: price and volatility, geopolitical situations and regulations in producing countries as well as market concentration. All of these concerns can have significant impacts on the costs of materials procurement.

When making production plans, manufacturers are confronted with multiple kinds of uncertainties, stemming both from the demand- and the supply-side. Demand variations usually require that manufacturers maintain product and material inventories; on the other hand, uncertainties in the supply of resources for production introduce another important set of issues. For some classes of supply risks, conventional business strategies and operational planning — such as contracting, hedging or stockpiling — are usually sufficient to mitigate the risks to manufacturers. However, when uncertainties affect the long-term reliability of the supply or arise from fundamental structural changes in supply or product technologies, the conventional economic understanding is that markets will “naturally” lead to efficient outcomes, provided that these markets are well regulated. For an individual firm, however, knowing that markets will ultimately lead to an efficient allocation is of little comfort when the consequences of price excursions or supply disruptions will directly affect the individual actors and their ability to satisfy demand — and stay in business. It hence becomes desirable to develop decision-tools that can help manufacturers better understand market dynamics

and supply-related risks, as well as the impact of different demand patterns on the price of needed resources.

What types of tools, then, can be used to identify supply uncertainties, since those uncertainties can have very diverse origins? In particular, firms typically rely upon prices as their main signals to inform their production and operational decisions when facing these uncertainties. This view derives from economic theories arguing that prices represent the true social cost of a resource, under conventional market assumptions. If the conditions of a perfect market hold, price should provide all the information necessary for firms to make efficient decisions. However, market imperfections, such as externalities or structural inefficiencies, can bias prices' accuracy in reflecting the implicit value of a resource. This suggests that a manufacturer's response to price signals should be tempered by a better understanding of the nature and source of those biases — for example, whether the price excursion derives from natural, geopolitical or logistical influences. As a consequence, firms seek to develop other indicators that are more finely tuned toward assessing the causes of price fluctuations, rather than relying solely upon prices themselves. Such metrics — for instance, market concentration indicators or depletion indexes — can be developed to assess different types of risks, as will be shown in this thesis. These metrics derive from models that have been devised to develop a deeper understanding of the fundamental interactions between supply and demand for a specific market, in order to better inform manufacturers making purchasing decisions. It has been observed, however, that only a few — if any — methods adopt an economist's point of view in order to study materials markets (Erdman and Graedel 2011).

This work presents a model that is grounded in economic theory and incorporates knowledge about the mining industry to understand market dynamics and imperfections. The main focus of this thesis is the supply of materials and the implications that public policies, market structures and demand scenarios have on production and price, and ultimately on manufacturers.

The specific case of *critical materials* has been chosen in this study. Materials characterized as “critical”, such as Rare Earth Elements (REEs) or precious metals, are elements of the periodic table that fulfill specific functionalities difficult to achieve using other technologies, and whose supply and prices have been subjected to variability, which dramatically affects production costs. The increased demand for such materials, particularly in manufacturing sectors such as the automotive industry or renewable energy, has increased the risks of supply disruptions, and manufacturers are more and more concerned about their availability.

The fact that the markets for critical materials exhibit high volatility makes them useful subjects for this sort of study — there is, therefore, a large number of observations that can be tested. Moreover, the attention paid to these materials markets means that considerable information, albeit collected after the fact, is available to construct and validate modeling frameworks. The aim of this work is to use the rich set of historical circumstances surrounding critical materials and illustrate how a model such as the one that has been developed can help better understand the influence of market dynamics on observed events.

The questions addressed in this thesis are the following: to what extent is it feasible and beneficial to adopt an economist’s view to get new insights on materials availability? In the context of critical materials, how can a better understanding of market dynamics inform criticality assessments and risk-mitigating strategies?

First, this thesis seeks to develop a characterization of what materials criticality means, and in particular confront current approaches to materials criticality with regard to the needs of manufacturers and policy-makers. The modeling tool that has been developed — the **M:5** model — is then presented. It has been grounded in economic theory, but also incorporates imperfections that are specific both to mining and to “real world” markets in general. Chapter 3 will explain the model and its assumptions, as well as compare it to existing modeling tools that have been looking at materials availability. Finally, model results are presented to illustrate how a dynamic approach to criticality enables better-informed decision-making when considering material purchasing. Moreover, different risk-mitigating policies, stemming from model results, are assessed in the context of the observation of real-world markets.

Chapter 2

Materials Criticality

This chapter introduces the notion of material criticality, which has been the context of this research. The example of palladium, one of the six Platinum Group Metals (PGMs), offers an illustration of how criticality can manifest itself in a particular economical context, and how a better understanding of sources of concern may lead to the development of efficient risk-mitigating strategies. Finally, existing approaches to the question of materials availability are presented and assessed in light of the scope of this research.

2.1 Introduction to the Notion of Criticality

This section addresses the question of materials criticality, and formalizes ways to identify and characterize associated risks.

2.1.1 Definition and Presentation of Critical Materials

The topic of materials criticality has recently received attention largely because so-called “critical” materials, such as rare earth elements (REEs) and platinum group metals (PGMs), are of increasing importance for many different sectors of the economy: automotive, environmental, energy-related, high-technology etc. For instance, REEs are used in permanent magnets to make wind turbines, and PGMs are essential in catalytic converters needed to reduce car emissions. Recent studies have established a list of critical elements that is shown on Figure 2-1.

When speaking of a critical material, analysts are usually referring to a material whose supply is constrained while demand is high, and whose market is global in scope. These two conditions lead to high market volatility and a perception of supply unreliability. The factors underlying these conditions, however, may vary widely from a material to another. Sometimes materials criticality might derive from geophysical scarcity, but criticality can also be the consequence of supply concentration or a monopolistic situation that creates substantial market pressures. The resulting uncertainty has a dramatic influence on the decision-making of manufacturers regarding materials purchasing and design choices, and the consequences on the economy as a whole can be great.

Figure 2-1: Critical elements according to recent studies (Jaffe et al. 2011; Bauer et al. 2011; Eggert et al. 2008) . In particular, PGMs are highlighted in yellow and REEs in green.

need for the material of concern. In fact, most definitions speak of criticality as the interaction between instability of supply and reliance upon supply. This characterization, however, does not provide specific actionable risk-mitigating strategies. This thesis aims at developing ways to identify criticality risks, and ways of characterizing criticality that are better guide for appropriate action, once a criticality risk is identified.

Criticality is traditionally associated with scarcity. This thesis argues that, despite its context-dependency, there are formal criteria that can be used to establish and classify a material’s criticality. More importantly, these criteria can serve as a guide to the strategic responses most appropriate to the context out of which criticality derives.

In particular, criticality is the consequence of a confluence of factors: *(a)* market imperfections in either materials production or consumption, or both; *(b)* the influence of non-primary market actors on the market, such as governments and investors; *(c)* the fragility of the resource supply chain to “common mode” disruptions arising from operating dislocations, either stochastic (e.g., natural disasters), organizational (e.g., labor unrest) or institutional (e.g., non-competitive behavior of firms such as cartelization); and *(d)* a relatively sparse set of feasible — or at least not cost-prohibitive — alternative technologies to achieve comparable functionality using different materials.

Firms facing these circumstances run the risk of facing extraordinary market volatility, both in terms of substantial price excursions and in terms of restrictions on resource availability at any price, which may ultimately lead to firm failure.

2.1.2 Functionality Constraints: Manifestation of Criticality from a User Perspective

When making design decisions, manufacturers seek to employ the least costly alternative that provides a given functionality, or alternatively choose the most efficient design under a cost threshold. This cost minimizing process leads decision-makers to consider a range of materials that could satisfy the set of design parameters that a product should fulfill. The concept of “demand for a material” is not meaningful in itself, at the economic level — rather, it is the demand for its performance that ultimately leads, in a complex fashion, to a derived demand for that material. This thesis employs the notion of *functionality* to encompass this complex dependency among the materials required, the technologies applied, and the resulting performance

of a manufactured good.

Figure 2-2 illustrates the way in which cost and performance targets shape how manufacturers make design choices. Performance thresholds are indicated by the red dotted line on the figure, and designate an upper limit on acceptable cost and a lower limit on acceptable performance. The figure represents the notion that design alternatives that have a cost above the threshold while offering a poor performance are not desirable; conversely, the alternatives whose cost and performance are represented by bundles in the green zone satisfy both conditions. Some technologies might also satisfy only one of the two conditions, and will hence require a “trade-off”: a company may elect to choose an alternative having desirable performance over higher (and less desirable) costs, if no cheaper alternative yields desired levels of performance.

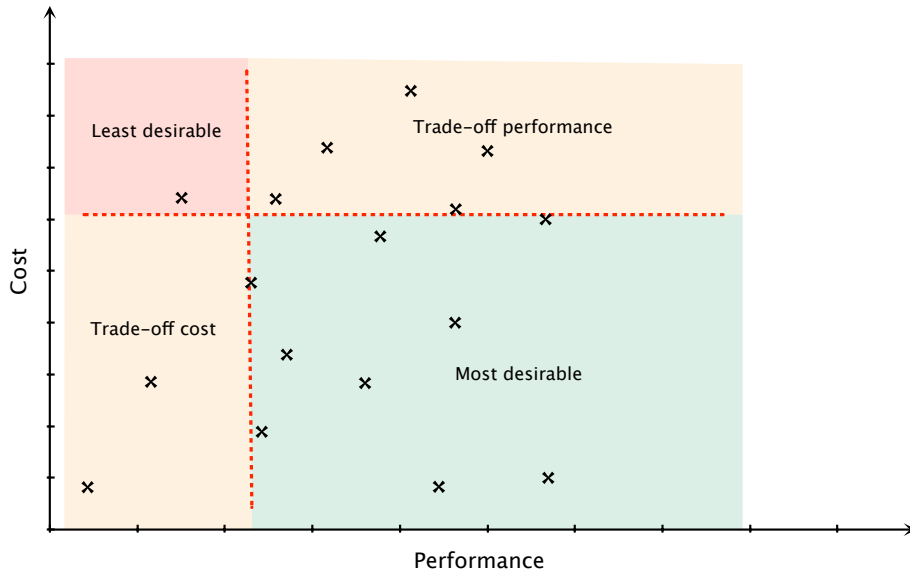


Figure 2-2: Space of possible design choices with cost and performance thresholds.

The need for rare earths in wind turbines for electricity generation exemplifies the notion of functionality constraint. The efficiency of a wind generator is a strong function of the magnetic field strength used in the generator, and the most effective magnets in current turbine designs rely upon rare earths magnets to produce these high magnetic field strengths. Hence, it is not the element itself that is sought by a wind turbine manufacturer, but rather its magnetic property. If an alternative existed at a lower price with similar properties, manufacturers would buy that substitute instead. In this case, because of the performance requirement and the absence of a suitable alternative, REEs are the only materials that satisfy the functional constraint at a feasible cost.

Substitutes can be represented on the cost-performance matrix presented on Figure 2-2. Selecting a material over another becomes a matter of choosing which (*performance-cost*) bundle — represented as a black cross on the graph — is most advantageous, in the sense that it affords the producer the highest profitability as well as provides the market a good that is attractive enough in terms of performance and social cost. In the case of critical materials however, the set of alternatives can be more limited and constrained in specific ways that lead to criticality. In a case where the supply for a specific material is unreliable for instance, its price may be subject to high volatility, hence making the optimization process more challenging. More importantly, the set of alternatives may not be as abundant as it is for a non-critical material; in particular, the functionality constraints might be predominant — in the case of REEs for permanent magnets for instance — and hence no other known material could fulfill the performance requirements.

Manufacturers need to account for criticality when making design and purchasing decisions, because supply risks and price volatility greatly influence the market's perception of availability. Failure to consider criticality might lead to situations, as in the case of palladium presented in Section 2.2, where historic price levels do not incorporate the notion that the supply for that material is constrained — for instance the market is highly concentrated — and that this may lead to disruptive events such as supply shortages or price excursions.

2.1.3 The Structure–Conduct–Performance Paradigm Applied to Critical Materials Markets

As stressed in previous sections, critical elements can be of high importance to the economy as whole. In addition to market actors — in particular material producers and manufacturers — other stakeholders may also have a large interest in the stability of the market. As a result, not only do materials markets influence a large number of stakeholders, but there can also be external influences on the market, exerted by actors outside the market, including governments.

The different markets for critical elements share common structural characteristics. In order to study the different interactions taking place in such markets, this section has adapted the Structure–Conduct–Performance Paradigm developed by Scherer and Ross (1990) to the critical material industry case. Figure 2-3 illustrates the different forces that take place in the industry.

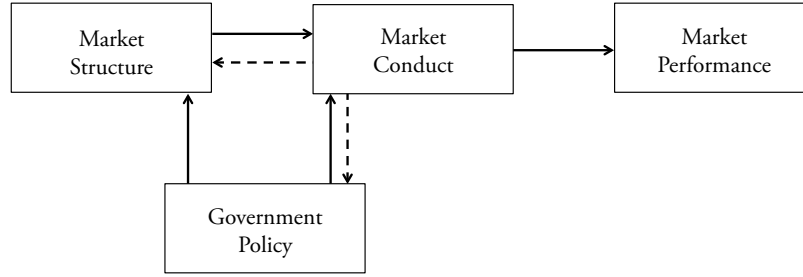


Figure 2-3: The major components framing of the political economy of a materials market, resulting from the Structure–Performance–Conduct paradigm. In particular, the arrows depict the ways in which the presented sectors influence one another.

The four main components of this framework are the market structure, conduct and performance, as well as government policy¹. The arrows on Figure 2-3 represent the influences exerted by the different blocks on each other, which will be described in this section.

The broad definitions of each of the four components are summarized below:

Market Structure encompasses the architecture of the market: the number (and concentration) of sellers and buyers, the barriers to entry (often very high in the case of critical minerals since the mining industry is highly capital-intensive), and the cost structures of the different suppliers and consumers — *i.e.* the individual supply and demand curves.

Market Conduct can be described, in the case of the mining industry, with firm pricing behavior, the potential for lobbying within the industry, as well as other structural components influencing the ways in which the market can behave — the notion of competitive advantage of different countries, for instance.

Market Performance can be described with the total materials production and the observation of whether the market operates at the point of allocative efficiency (*i.e.* where marginal cost is equal to marginal benefit). Price volatility, supply reliability and supply constancy are good indicators to assess the overall performance of the market.

¹One could also include the basic conditions of the market — namely the description of supply and demand general characteristics, such as the physical constraints surrounding the material or the price elasticity of demand. The scope of this study however is limited to the four main components of the paradigm.

Government Policy in the case of materials markets can take the form of taxes and subsidies, international trade regulations, mining and environmental regulations, controls on the price of the commodities, or regulations against antitrust as well as mandatory disclosure of information.

Because critical elements are important to a wide array of actors, the interactions among these four components will be large in number and diverse in their influence. Mapping them affords certain insights into the behavior of these markets.

Market Structure::Market Conduct The supply market for mineable materials is generally highly concentrated — REEs are perhaps the most striking example, since 97% of the global supply is mined in China. Moreover, barriers to entry are very high in the mining industry, largely because of high investment costs and physical constraints. Monopoly or oligopoly may hence arise and lead to non-competitive market behaviors. The monopolistic situation of China for REEs mining has given the country very strong bargaining powers, and the recent REE “crises” — in particular the setting of quotas and disruptions in the supply (Bradsher 2010) — have arisen because of this inherent inefficiency in the market structure. On the other hand, a concentrated demand side can lead to monopsony or oligopsony situations where a narrow sector dominates market demand. This can potentially increase the risk of lobbying by the main demand sector. Finally, extraction, refining and parts of the manufacturing phase can be vertically integrated for certain materials — it has recently become the case for the permanent magnet industry using REEs for instance. The bargaining power of one market actor may hence significantly increase and shift his behavior away from what would be expected in a competitive market.

Conversely, the conduct on the market may also have an impact on the structure: demand sectors might drop out, or suppliers leave the market because of an aggressive pricing strategy that can be adopted by others. Again, the case of REEs is striking: the monopoly situation observed until today mainly rose because other actors were driven out of business around 1985 when China increased its supply very significantly and drove prices down (Hurst 2010).

Government Policy::Market Structure Public policies may have a direct impact on the market structure, and this by different means. On the one hand, a material can be strategic to a government because of potential security implications; as a result, the government itself may become a consumer and directly change the

structure of demand. On the other hand, policies can alter the very structure of the supply. First, governments can put in place antitrust regulations; in the case of critical materials however, this lever can be limited in that the sometimes highly concentrated situations on the market are due to either physical limitations or the high financial barriers to entry. Governments may also have an incentive to provide financial benefits to potential new entrants — via the use of subsidies or specific taxation regimes for instance — and hence encourage the development of new mines that can alleviate the concentration of supply. Finally, governments might be able to sanction reprovved supply practices by regulating the sources of supply. The Dodd-Frank Act indeed requires all American manufacturers to report any use of one of the 3TG materials (tantalum, tin, tungsten and gold) emanating from the Democratic Republic of Congo in its “Conflict Minerals” Rule (Dodd-Frank Act (2010)).

Government Policy::Market Conduct Different types of policy tools can be used by governments to regulate critical materials markets and change their actors’ behavior. One type of actions is the implementation of price controls; governments may choose to either set a floor or a ceiling on the commodity price if they have sufficient authority, or to subsidize partly for the cost if the material is deemed of high importance for national economy. Mining regulations may also be put in place so as to limit unreasonably high extraction rates that have a negative impact on *(a)* the environment, *(b)* the labor force and *(c)* other actors on the market that cannot operate at such high extraction rates. Public policies can also tackle the question of asymmetric information on the market, which is a source of imperfections, and reduce this asymmetry by mandating information disclosures by suppliers — either directly or inferred through data collected from the firms comprising the overall industrial sector. Finally, regulations can be influenced by market actors who may benefit from a regulated environment, since they are usually better organized and have a greater influence on the political aspects of the economy. This can however weaken the efficiency of the markets, because of possible regulatory capture by private actors (Stigler 1971).

Market Conduct::Market Performance According to economic theory, the key conditions of a perfectly competitive market are that information is perfect, that actors behave rationally and homogeneously, and that there are no frictions or transaction costs. Under these conditions, the market-clearing price should reflect the intrinsic economic value of the resource. As pointed out earlier, some market behaviors in the case of critical materials may lead to inefficiencies and

violate the assumptions of a perfectly competitive marketplace. The inefficiencies that then arise — whether from the nature of the market, from the market conditions specific to the material, or from external events such as conflicts — can have an impact on the overall performance of the market. Events such as supply disruptions, price volatility, or negative externalities, are direct consequences of those imperfections and can have dramatic impacts on the economy.

The market for critical materials presents systemic characteristics and inefficiencies that make the supply chain for the resource vulnerable to risks such as supply disruption or high price volatility.

2.2 Illustration of the Concept of Criticality: the Example of Palladium

One of the most acute market imperfections for critical materials is the incompleteness of information. The supply for critical materials is concentrated in a limited number of countries, while their market is very often global. Concentration gives supplying countries additional bargaining power at the international level and increases the dependence of importing nations on the information coming from a limited number of major actors. Manufacturers have to plan their expected consumption for the upcoming year and order an adequate quantity from the exporting countries. Contracts (short- or long-term, depending on the producing countries) can be established, but supply disruptions are possible. Furthermore, the global demand for one material in a year can be challenging to estimate for market strategists, since it depends on technological changes, new regulations — such as CAFE standards that raise the need for PGMs in catalytic converters — investors, price etc. The incompleteness of information — and in particular the asymmetry of information concerning the supply the limited understanding of mine operations and deposits by manufacturers — leads to inefficiencies on the market.

Palladium, one of the six PGMs, is an interesting example of critical material. In particular, the “Palladium Crisis” of 1998 provides a good illustration of a specific aspect of criticality, namely that of asymmetry of information perpetrated by an actor of the supply duopoly for the material, combined with an unprecedented increase in demand.

The following sections use the palladium case to illustrate how ‘criticality’ should

be studied specifically in order to identify the different causes and interactions that led to a critical market.

2.2.1 The “Palladium Crisis”: Origin and Implications

Figure 2-4 illustrates the fact that palladium prices have *historically* been lower than platinum prices. As a result, car manufacturers progressively changed the design and PGM formulation of catalytic converters in order to use more of the less expensive palladium as a platinum substitute (both PGMs have similar catalytic properties, although platinum is not fully substitutable). Moreover, around 1997, car manufacturers agreed to more stringent emission standards, leading to further significant increases in their use of palladium in their fleets.

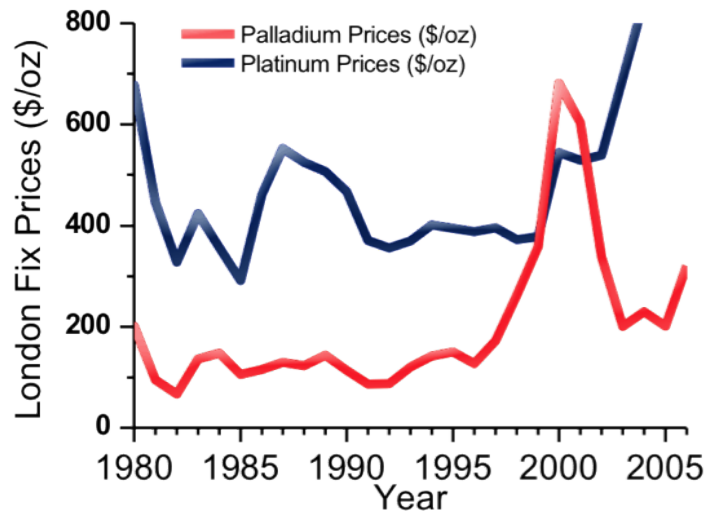


Figure 2-4: Historical prices for palladium and platinum. *Source: Kitco.*

Yet that year Russia, the leading palladium exporting country (representing about 46% of the global supply), decided to freeze exports until early spring. The resulting supply shortfall created high tensions on the market and initiated a price increase. The following year, the Russian government imposed export limits again, this time until summer. Manufacturers — automakers in particular — increased their demand for the metal, in order to mitigate the risk of disruption in the future, and consequently accumulated stocks of excess palladium. Speculation further increased market pressure, and prices rose.

When the anticipated supply disruption did not take place and demand shifted away from palladium — some industries managed to reduce their demand by design changes that proved very costly — the price of palladium dropped abruptly and manufacturers with large inventories of unused palladium incurred major losses. To give a sense of the magnitude of these losses, one major US car manufacturer lost over one billion dollars during that crisis — and on average, less than an ounce of palladium is used in a car.

This crisis illustrates how the combination of different events made palladium particularly critical:

On the one hand, expectations of actors were not met, in that the past proved insufficient to inform the future behavior of the market. Indeed, the demand for palladium increased significantly around that time, mainly due to the early and rapid adoption of stringent new emission regulations by car manufacturers that expected palladium supply to be abundant enough to meet their needs — as had always been the case by the past. When the Russian government cut the supply, the demand could not be met, the other sources of supply (mainly South African and North American less significantly) proved insufficient to sustain the surge in demand, leading prices to rise.

On the other hand, there was a significant asymmetry of information concerning the Russian supply.

The first manifestation of it came from the quotas set by the government. It should be noted that all of the Russian primary PGMs supply comes from the Norilsk nickel mine (of which PGMs are byproducts). Furthermore, all the exports have to be processed through *Almazjuvelirexport*, a federal state-owned unitary enterprise, exporting precious metals on a commission basis. The supply cuts that occurred in 1997 and 1998 had been publicly justified as resulting from paperwork processing issues within the governmental instances. The government hence played an important role in the supply disruptions that occurred at that time and did not provide sufficient and accurate information about the quotas that had been set — in a timely fashion for decision-makers to make informed purchasing decisions.

The second very important source of incomplete information in the case of the Russian palladium supply is the existence of a strategic stock in Russia. In the 1970s and 1980s, during the Cold War, a lot of palladium had been extracted in the nickel mine. Yet at the time, the demand for palladium was very slim and trading that precious metal only seemed secondary in the eyes of the soviet government. As a result, important quantities of that material got piled up in national reserves and remained there under state secrecy until the growing need for palladium provided an incentive to

the Russian government to start trading that stock. In the years preceding the crisis, palladium had been flowing out of that stock as well in order to meet growing export requirements. But the quantity remaining in that stock had always been treated as a very important state secret, and manufacturers importing Russian palladium did not know exactly how much metal was left. Hence, purchasing teams were planning their import quantities based on the supply from previous years and accounting for the strategic stock to fulfill their needs. This lack of information and transparency from Russia only further increased the negative effects of the crisis, and speculators used it in order to deepen the pressure on the market and palladium prices.

In this case, criticality arose because of the combination of different factors. First, the historical demand data was not sufficient to inform future consumption because of radical changes in the automotive industry that led to a significantly higher reliance on palladium. Second, uncertainty surrounded the Russian exports, since the government set export quotas and the magnitude of the stock remained (and still is today) unknown. This asymmetry of information became egregious because Russia was responsible for a large part of the global supply.

Uncertainty surrounding both supply and demand, led to very high price volatility, market instability — worsened by investors — and ultimately encouraged the development of North American mines (Stillwater in particular) so as to ease the market concentration.

2.2.2 Risk-Mitigating Policies that were Implemented at the Time

On the one hand, palladium consumers implemented different policies to mitigate the risks and the impacts on the market.

First, manufacturers decided to stockpile when Russia announced supply disruptions. This policy turned out to be very harmful because that stock was constituted when the price was rising, but it quickly fell at its original level, hence significantly devaluating the investment made by the manufacturers.

Then design choices were made so as to move away from palladium as quickly as possible; some car manufacturers developed very expensive new design strategies to be able to meet newly established stringent regulation standards without using as much palladium. Similarly, electronics companies tried to reduce the amount of palladium used. Because the decisions were made very rapidly and changes had to be implemented sometimes in less than a one-year period, these changes were very

expensive to implement.

Achieving increased recovery and recycling of palladium might have been an efficient policy, since a secondary source of supply tends to mitigate supply disruption risks. However, that could not be put into place at that time because the widespread use of palladium in car was a very recent development. Without a stock of obsolete product from which to extract material, there was no palladium to recycle.

The supply side also put different policies into place. In 1999, the Russian government authorized long-term contracts (10 years) with automakers in order to ease the market panic, and lifted the quotas on primary exports. Exports from the stock had to be individually reviewed, but that measure eased the market to a certain extent. Finally, investors decided to expand the Stillwater mine, while other sources of supply emerged (in Canada and Zimbabwe), reducing market concentration via a “natural” market structural change.

2.2.3 Proposed Policy Options to Lower the Impact of Information Asymmetry on the Market

The market for critical materials, and palladium in particular, typically owes its concentration to natural causes: not every material can be economically extracted everywhere, and opening a mine represents a massive investment. As a result, first-movers and countries where a material is particularly abundant and easily mineable have a definite strategic advantage. Russia is a major player in the market for palladium, and hence greatly influences it. The Russian government has had a strong influence on the treatment of palladium exports, which has increased the asymmetry of information concerning quota setting as well as quantity of stock remaining. Indeed, all exports have to go through one state-owned company and every transaction has to be approved by the government. Moreover, the paperwork and export approvals required to unfreeze the Russian supply were a very good example of what Allison (1969) qualifies as organizational inefficiencies: the government had to follow the pre-established the “standard operating procedures” despite the exceptional circumstances created by an increase in demand, which limited the choices and hence the strategies that could be adopted. Other governments cannot intervene to directly reduce the information asymmetry however — especially because Russia was not in the WTO at the time (it entered in August 2012) hence limiting the bargaining power of the international community.

Different public policies can be considered in order to mitigate the risk created

by the asymmetry of information. The first one is aimed at reducing the information asymmetry by gaining more control over supply information; this can be accomplished by the opening of a new mine — if the reserves exist — in an importing country, since possessing a domestic source of an expensive commodity can prove very strategic. This is what happened in the United States with a significant expansion of the Stillwater mine under a federal mining law that provides subsidies for purchasing of public land. The main drawback of this policy is the very high upfront cost it requires — not necessarily by the government, but by the investors building the mine. Hence it is not always a feasible option. Another way to accomplish that same goal yet to a lesser extent could be through the investment in an existing mine that would not have to be domestic, hence providing a greater control on the operations of the mine. It would be challenging to implement since mining countries may not accept other governments' investments, but could potentially be accomplished by private companies.

Another type of policy would be the creation of a federal stock of the materials deemed strategic. Of course, with this policy come the drawbacks of the risky investments and it can be seen as an overregulation of which the costs might exceed the benefits, if the investment proves hazardous.

One could also envision the negotiation of governmental contracts for the regulation of imports/exports that could act as insurance policies for domestic manufacturers in need of a critical material. Yet such a policy would require an important amount of coordination amongst the nations, which could be problematic in cases similar to the one we just studied where it seemed that coordination was lacking even within the Russian government to get the different approvals. Moreover, one could argue that such an insurance policy would be risky for a government to take on, and should be implemented only if the material impacts industries that have a strategic role in the domestic economy. The strategic importance of PGMs and the impact it has on several industries — including high-technology industry — could lead governments to, in fact, take action. It could however increase the risk of a Stiglerian regulatory capture (Stigler 1971) by industries that are in need of a specific material, since those interest groups would benefit from regulations favoring their own industry through subsidized raw products, as compared to others that may not need the same materials.

Finally, asymmetry of information could be eased by structures in charge of monitoring extraction and demand evolutions. Certain organizations, such as Johnson Matthey for PGMs or the United States Geological Survey (USGS), publish periodical reports and data about the state of the market of various materials. Yet these reports usually provide a short-term outlook on both production and demand, which does not provide sufficient information for decision-makers to make purchasing decisions in

a timely fashion. It would hence be beneficial to have an international third-party organization that publishes comprehensive reports with longer-term considerations to help industries make decisions about materials.

Asymmetry of information in the context of extraction of critical materials is an important source of market failure; mitigating that risk can prove challenging when the supply is controlled by the government of main suppliers. However some public policies can be put in place within importing nations so as to limit the impacts on manufacturers and, were the mines not directly controlled by the government, policies within mining countries could be implemented in order to maintain minimum contractual exports, which could be supported by the WTO for instance. In any case, appropriate risk-assessment should be developed.

The example of palladium, and more specifically of the 1998 “Palladium Crisis”, is an illustration of a specific case of criticality. Indeed, palladium became critical around that time because of an increased demand — fostered by the automotive industry and tightened emission regulations — as well as a complex and uncertain supply stream emanating mainly from Russia. This example hence illustrates a specific aspect of what we previously defined as materials criticality.

2.3 A Review of Existing Approaches to the Question of Criticality

The notion of *criticality* has been formally addressed only recently (Erdman and Graedel 2011) — resource scarcity had been widely studied in the past, but the notion that factors other than depletion can affect the reliability of materials’ supply has only emerged recently, with the manifestation of large economic crises such as the one presented in Section 2.2.

This section will present an overview of existing criticality-assessment methods, and illustrate where this work adds to the existing body of methods.

2.3.1 Past Work on Material Criticality

General Considerations

The notion of criticality is difficult to formalize, since, as mentioned earlier, it is very subjective; however existing approaches agree on a fundamental issue, namely the fact

that criticality is a manifestation of a supply risk and of a vulnerability to this risk (Graedel et al. 2011; Bauer et al. 2011; Jaffe et al. 2011).

The question of supply risk is now widely recognized as not limited only to scarcity (as mentioned in the report *Critical Raw Materials for the EU* 2010). Instead, other considerations (such as geopolitical risks or sustainability concerns, as presented by Graedel et al. 2011) are often mentioned when assessing the question of supply risks comprehensively. The sources of concern that are highlighted in recent works can be very diverse: including relative physical availability (often evaluated by the USGS²), feasibility of extraction, regulations and societal characteristics of producing countries (Graedel et al. 2011, mentions the Human Development Index for instance), and geopolitical considerations that can be measured using metrics such as the HHI³. Most approaches tackle the issue of supply risk assessment through the construction and use of metrics, presented in the next section.

Another important notion for criticality is that of the “functionality constraints” that we mentioned in Section 2.1, or vulnerability to risk. This notion is often addressed by defining the scope of the study, and in particular by specifying who the stakeholder is and what his specific current or projected demand for the material is — the scope is determinant in deciding which materials are critical and which are not (Erdman and Graedel 2011). The question of materials substitutability is also very important for manufacturers, since it directly feeds into the design decision-making process, and is hence helps to establish the demand-related risks of a material. Another important aspect of demand risks is the structure of the demand — more specifically, the concentration of demand sectors, and the resulting market power of suppliers over a specific decision-maker.

Finally, the notion of time dependency of criticality assessment is cited as an important consideration (in the report Bauer et al. 2011, for instance). A critical assessment has indeed a short ‘lifetime’, since the context in which it is established is subject to evolving influences. Therefore, criticality assessment must be regularly updated to reflect changing market contexts.

²United States Geological Survey, a scientific American agency that study among others natural resources

³The Herfindahl–Hirschman Index that measures the relative competition of firms in a market by comparing individual sizes to the industry as a whole, and defined in the following section.

Metrics-Based Approaches

A large portion of the literature on criticality relies on the use of metrics, to assess the criticality risks presented by a specific material. In these analyses, the decision-maker collects relevant data and computes different numerical indicators that indicate to what extent a particular aspect of the market presents a risk.

One of the particularities of such approaches is the ease of computation, since the data necessary to calculate such metrics can be found in publicly available sources, such as the annual reports of mining operations or surveys such as the United States Geological Survey (USGS). Another type of resource can be annual overviews of a specific market by private consulting firms — for instance Johnson Matthey for PGMs.

Moreover, a decision-maker can easily refine such a risk assessment to his requirements by choosing the metrics that are most relevant to his activity and need, as well as setting the appropriate thresholds that lead to declaring that the material is critical for his firm, or not. This degree of customization makes a metrics-based criticality assessment particularly flexible, as well as quick.

Examples of metrics that are often cited and used are listed below:

Herfindahl-Hirschman Index is a measure of the relative concentration of either the supply or the demand and that can be expressed as a percentage. It is defined as

$$HHI = \sum_{i=1}^N x_i^2$$

where x_i is the fraction of the total supply (or demand) the i -th supplier (or consumer) is responsible for, and N the number of actors currently on the market. Agencies commonly consider markets whose index is below 15% to be non-concentrated, between 15 and 25% to be moderately concentrated, and above 25% to be highly concentrated (refer for instance to DoJ 2010).

Exponential Index of Depletion expressed in years, and introduced by Meadows et al. (1972), is the time it would take to consume the supply at a constant exponential growth rate of consumption. It assumes in particular that discovery and recycling rates are negligible. The formula is

$$y = \frac{1}{\rho} \cdot \left(1 + \rho \cdot \frac{R}{C_0} \right)$$

with y the number of years of consumption left at the constant rate ρ , R the reserve left of the material and C_0 the annual consumption during the initial year.

Recycling Rate is the percentage representing the amount of material that can be recovered in terms of material consumed. More specifically,

$$r = \frac{\text{scrap consumption}}{\text{total consumption}}$$

Other metrics can be evaluated to assess scarcity, price volatility, cost of substitution etc. Alonso (2010, Section 4.2, pp 59–63) provides metrics of interest to evaluate material availability.

Existing Models Addressing the Issue of Materials Availability

Another type of criticality assessment focuses on the question of materials availability, taking a more “dynamic” approach than metrics. Different types of models have been devised to understand and assess the behavior of materials markets, the most notable being analytical models based on economic abstraction, econometrics models using financial data, and simulation tools such as system dynamics models.

The complexity of materials markets make this modeling task challenging — especially because of market deviations from ideal, theoretical behavior. As a result, a decision-maker may choose a certain model that satisfies his own “performance-to-effort” ratio requirements, since adding complexity to a model requires additional effort and time. The key aspect of those model-based approaches is, thus, the proper assessment of what insights are desired and what level of precision should be achieved in order to fulfill these requirements.

Section 3.3 will delve into greater detail to explain what each of these methods comprise, and what type of insights can be gained from their use.

2.3.2 An Example of a Metrics-Based Framework to Assess Criticality

This section provides the example of a metrics-based approach that has been developed at the Materials Systems Laboratory at MIT by Elisa Alonso *et al.* that has been

applied during this research work in order to quickly evaluate the criticality of different materials for a manufacturer.

Five main sources of risk — both on the supply- and the demand-side — have been identified, and provide a comprehensive outlook on a material. The potential areas of concern evaluated for each material are shown on Figure 2-5: physical constraints, institutional inefficiencies, sustainability impacts, relative importance to the industry and importance to the company. The following section will describe each category in greater detail.

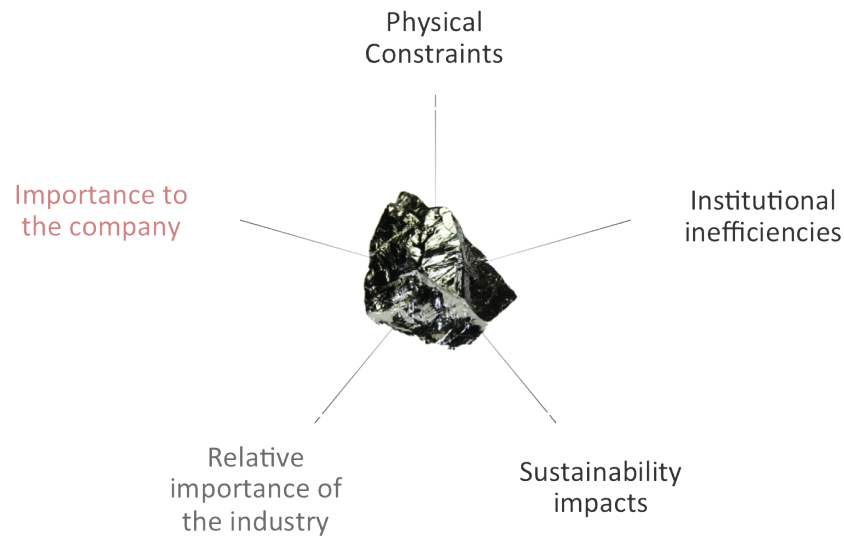


Figure 2-5: Schematic representation of the developed criticality-assessment framework. The five factors represented here, namely physical constraints, institutional inefficiencies, sustainability impacts, relative importance to the industry and importance to the company, have been identified as the main sources of risk employed in this particular form of metrics-based criticality analysis.

Assessment of Supply Risks

Physical constraints First, physical constraints associated with the material are evaluated. This component of the analysis looks at considerations such as the crustal abundance of the material and the amount of energy required to extract it — both of which have an impact on production cost and ultimately on which actors can enter the market. Another important aspect is the question of whether the material is a by-product of another resource or if it is a primary material,

since production economics can also be significantly influenced by the market of co-products, which further complicates the risk-assessment.

Different metrics can be developed to assess such characteristics (Alonso 2010), including the static and exponential depletion indexes (Meadows et al. 1972), and relative rates of discovery and extraction (Malthus 1798; Gordon, Bertram, and Graedel 2006).

Institutional inefficiencies Another important factor in criticality assessment is the notion of institutional inefficiencies. These include the question of supply concentration as well as the different geopolitical risks of the producing countries. Indeed, a supply disruption can occur without a physical shortage of a material, but rather because of a conflict or strikes, for instance. A recent example is the case of platinum, where strikes by South African miners have disrupted the production for several months (see for instance the USGS report by Yager, Soto-Viruet, and Barry 2012).

Again, metrics can be developed to assess such risks. An important one is the HHI described in Section 2.3.1. In particular, higher values of this index indicate a higher market concentration, and possibly a higher risk of disruptive events for price and supply. Another consideration is the distribution of reserves among countries (Chapman and Roberts 1983). In particular, a greater concentration of reserves leads to greater production concentration and hence increases the risk of institutional inefficiency.

Sustainability impacts This last supply-related area of concern seeks to embed sustainability concerns in the evaluation. Critical materials typically are non-renewable mineable resources; as a result, issues of sustainable use can become important since unsustainable practices (whether perceived or actual) can potentially exacerbate or mitigate supply disruption risks.

One example of the influence of sustainable practice upon criticality is recycling. Some materials, such as precious metals in catalytic converters, can be recovered and, after processing, reused; if a recycling stream is properly set up, this creates a secondary source of supply (usually available at prices lower than virgin material) that can help mitigate primary supply risks. Similarly, a material’s carbon footprint can be an interesting metric of sustainability because of environmental regulations that can constrain manufacturers. Finally, certain materials are classified as “conflict minerals” by section 1502 of the Dodd-Frank Act (2010).

The concerns raised by the so-called conflict minerals (namely tin, tungsten, tantalum and gold) are due to their mining in the Democratic Republic of Congo. In particular, their retailing price is significantly lower than the ‘social cost’ of the resource because the workers are paid largely below a living wage. Moreover, the revenues of the mining are used towards financing armed movements, and there is a high risk premium associated with this supply. These reduced prices ultimately lead to market disruptions that upset the “socially efficient extraction rates” as well as promote human misery by sustaining conflicts and encouraging abusive mining conditions.

As with the preceding indicators, metrics can be used to help quantify contribution of sustainability to the criticality assessment. For example, the recycling rate of a material, paired with the lifetime of products using this material and life-cycle assessments, can be used to construct indicators of resource sustainability or efficiency. Other metrics of interest are the water-use of the mining process, as well as the carbon footprint of the material production.

Assessment of Risks on the Demand Side

The notion of criticality is inherently subjective, and dependent upon the decision-maker and his strategic intent. While supply risks are common because of the existence of a market, demand risks are assessed based on the user’s activity, which is illustrated below.

Relative importance of the industry First, it is important to assess the current demand landscape, in order to understand where the demand for a material comes from and what the characteristics of the different sectors are, such as the growth rates, elasticities — to understand the impact of changes in price on the demand of the sector — as well as recycling rates undertaken by the different industries. The relative importance of the decision-maker’s sector within the whole demand landscape, as well as the potential existence of high elasticity sectors that can act as “buffers” when price peaks, can also influence the firm’s decision.

Once again, the HHI index can be used to assess the concentration of the market, this time from a demand perspective. Indeed, the formula presented in 2.3.1 can be applied to demand sectors, with x_i the fraction (in %) of the total

consumption that is initiated by the i -th demand sector. Mono- or oligopsonistic markets are more vulnerable to changes in demand, and hence more subject to price volatility (Alonso 2010).

Importance to the company Finally, a specific firm should assess its current and projected need for a material. This assessment can also be a valuable basis for comparing a firm’s competitive position with others, since the effect of a price excursion or a supply disruption will differentially disadvantage the more dependent competitor.

Application of the Framework to the Example of Palladium

In order to demonstrate the application of the aforementioned framework, the viewpoint of a car manufacturer is presented as an example, examining the criticality risks deriving from the use of precious metals in vehicle catalytic converters. The data used comes from publicly available sources (see, for instance, the regularly updated USGS section for PGMs; see also Johnson Matthey Market Data).

Physical constraints Like the other PGMs, palladium is one of the most expensive materials by weight, since it is only found in low concentrations and requires substantial amounts of energy to extract. Its price is thus particularly susceptible to changes in energy costs. Moreover, palladium is often a by-product, either from platinum extraction in South Africa, or in the Russian nickel extraction by Norilsk. Finally, according to 2009 data from the USGS, the static depletion index for palladium is of 364 years.

Institutional inefficiencies In 2012, about 43.5% of the production of palladium was Russian, 36.5% was South African, 13.5% came from North American mines, 4% from Zimbabwe and 2.5% from other sources⁴. The resulting supply HHI can hence be computed:

$$HHI_{Pd}^{(2012)} = 0.435^2 + 0.365^2 + 0.135^2 + 0.04^2 + 0.025^2 = 34.3\% > 25\%$$

The supply for palladium is hence highly concentrated, according to the common norms for the HHI (DoJ 2010).

⁴Source: Johnson Matthey Market Data

As mentioned in Section 2.2, this high concentration as well as the Russian geopolitical landscape have led to supply disruption and high price volatility in the past. Moreover, recent strikes in South Africa have added pressure on the market⁵.

Sustainability impacts Russia mainly relies on nuclear, hydropower and natural gas to produce its electricity; however, given the high energy needed to extract palladium, as well as South Africa’s reliance on coal-powered electricity generation, the palladium’s carbon footprint is very large. Recycling mitigates this footprint somewhat, especially because the recycling of palladium is fairly efficient and well-established. Moreover, its use in catalytic converters also helps reducing NO_x and CO₂. Finally, palladium does not pose significant conflict mineral risks.

Relative importance of the industry Recent growth in car sales in Europe and South America has driven up the palladium demand for 2011 (a 6% increase). Moreover, the increasing Asian production of gasoline vehicles is a major influence on palladium’s prices. Although the demand for palladium in the chemical and electrical industries has risen, the automotive industry still constitutes the main demand driver for this metal. Jewelry demand is forecast to decrease as palladium prices rise, acting as a “buffer” sector to a certain extent, and hence lowering the impact of price excursions or other supply disruptions on other demand sectors.

This cursory criticality assessment, based on metrics and qualitative data, and to be completed with the specific needs of a given manufacturer, illustrates the criticality of palladium as a material used massively in the automotive industry as well as in other sectors.

While the resulting risk-profile for palladium is useful to quickly realize that palladium can, indeed, be critical if the firm’s demand for that resource is significant, the scope of this assessment is limited, since only static measures are considered. In particular, devising well-informed mitigation strategies can be challenging with only metrics-based considerations. Section 2.3.3 below addresses in greater details the general limitation of metrics-based approaches, such as the one presented here.

⁵A report on the impact of the strikes on the PGM industry has been published by the USGS (Yager, Soto-Viruet, and Barry 2012). An interesting analysis focused on palladium has also been published by Thomson Reuters GFMS (2013).

2.3.3 Addressing the Gaps in the Current Approaches to Criticality

Limitations of Static Approaches

The metrics-based approaches present the very significant advantage of being easily computable, easy to compare, as well as requiring a limited amount of data. However, they present several drawbacks that reduce their efficiency at comprehensively assessing materials' criticality.

First, metrics are inherently static. Some metrics may include a dynamic aspect by considering several years and including discount rate considerations, such as the dynamic depletion index. Nevertheless, metrics can only be evaluated at one point in time and hence cannot capture the existing complex interactions among supply, demand, and price. Section 4.2 will provide examples of situations when static metrics approaches are limited, and when the use of a dynamic approach such as a model can help better inform a decision-maker about the market.

In addition, the use of metrics requires a decision-maker to decide *(a)* what metrics to use and *(b)* where to set the thresholds to establish that a material is critical. It is incumbent on the decision-maker to make such “judgment calls”, which can be difficult to make consistently. Moreover, changes in market circumstances may require the establishment of new thresholds, or the use of different metrics. As a result, metrics-based approaches may need constant revision, not only to modify the context as for other criticality-assessment methods, but also to adjust the framework itself. Moreover, metrics may not be sufficient to comprehensively understand market dynamics and resulting risks.

Limitations of Existing Modeling Approaches

Section 3.3 will provide a more detailed overview of the limitations of existing modeling approaches, but the main issues are that most of the tools developed are either too data- and resource-intensive — especially system dynamics tools — or use an economic abstraction that neither accounts for market imperfections, nor provide the short-term vision that may be required by manufacturers.

Proposed Method to Address These Concerns

Metrics are a quick and easily computable way of assessing materials criticality, by evaluating the extent to which a material presents a given risk. Yet such approach is inherently static and ignores market dynamics that can take place and exacerbate or mitigate risks that would be harmful to a manufacturer.

While modeling tools are inherently limited in that they cannot fully replicate reality and might be extremely resource-intensive, they can address many of the limitations of metrics-based approaches. They can at a minimum be used to augment and complement these analyses by affording further insights. The question arises of the trade-off between the amount of effort required to build the modeling tool and the quality of insight that can be extracted from its use. Depending on a decision-maker's needs and the scope of his criticality study, different models may be favored over others. Yet it is not always straightforward to assess the criticality of multiple materials, since it may require a large amount of effort.

Based on those considerations, this work proposes a two-tiered approach to the assessment of materials criticality and the development of risk-mitigating policies that can be implemented by a decision-maker.

- First, a risk-profile of the material can be easily developed by using a framework similar to the one described in the section 2.3.2. This will enable the decision-maker to quickly assess, with the use of publicly available data, whether or not a material presents a potential risk to his activity.
- Then, if the risk is deemed significant, a market model has been designed to *(a)* use economics theory to understand market dynamics, *(b)* incorporate market imperfections that will improve the realism of the model and *(c)* use only a limited amount of data and be sufficiently flexible, in order to be applicable to different materials. The tool has been built in particular to make it easy for its user to compare different scenarios.

The following chapter presents the modeling tool that has been developed to answer the need for such a modeling tool, which addresses the different concerns of metrics-based approaches and adds to the existing modeling approaches.

Chapter 3

Methodology

This chapter introduces the modeling tool that has been developed in order to tackle the question of materials criticality while taking market dynamics into account. This tool, the Materials Mining Market Model for Manufacturers (or **M:5**) has been grounded in economic theory, but also incorporates the knowledge we have of mining markets and, in particular, accounts for some types of market imperfections. Moreover, the model has been built so that it requires only a limited amount of inputs, making it equally applicable to a wide range of materials markets. Finally, the model was built on a spreadsheet platform for accessibility.

In the following description of the modeling methodology, we will first present the economic reasoning used to build the model, as well as the different characteristics specific to the mining industry that have been implemented in order to capture characteristic market imperfections. Then the tool developed will be compared to other existing models that also describe materials market, and the practical as well as theoretical differences that can be observed will be discussed. Finally, this section will present the implementation of the model, as well as the assumptions used.

3.1 Model Design Philosophy

This section addresses the motivations that lead to the elaboration of the **M:5** model, especially concerning the construction of the supply curves and the market-clearing mechanism.

3.1.1 The Notion of Coherence and Correspondence in the Modeling Approach

This modeling effort seeks to overcome the microeconomic inconsistencies of conventional approaches that will be presented later in this chapter, in Section 3.3, with the objective of replicating observed market behavior without a major data collection and reduction effort.

More specifically, this approach was taken in the hope that more closely hewing to microeconomic theory would not only include the ability to defend the model on the basis of its stronger theoretical foundation, but also would yield a model requiring less data — which is characterized by Hammond (1996) as *coherence*-based research.

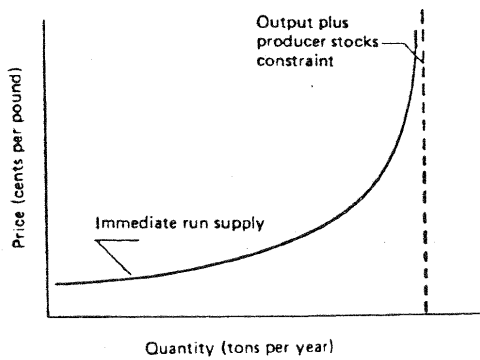
Yet, as will be explained in Section 3.3.1, modeling approaches purely based on economic theory do not fully answer the questions a manufacture may have on a materials' market, since they are abstractions of an idealized “rational” market. More correspondence-based approaches may therefore be required to elaborate complex modeling tools, adding real-world data and observations. The risk of such approaches however, as mentioned in Section 3.3.3, is that they may be too data-intensive.

As a result of this trade-off, the **M:5** model has been built from a coherence perspective, while adding a limited amount of real-world data and observation to achieve adequate correspondence.

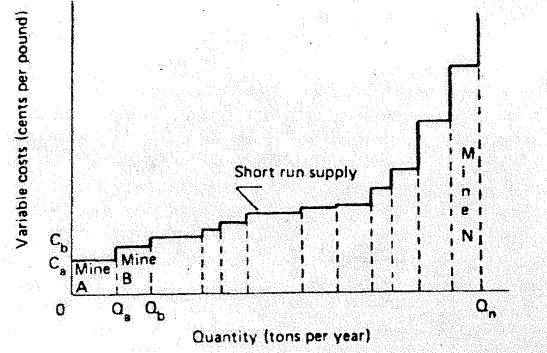
3.1.2 Reflections on Supply Curves

Conventional modeling frameworks for natural resource markets, particularly mining-based markets, construct a conventional upward-sloping short-run supply curve, by disaggregating supply by mine and using a “stair-step” approach (Tilton 1992). In this type of approach, the supply curve relies upon the assumption that an individual supplier will produce up to a certain quantity at a given — and, hence, constant — cost. Beyond that quantity, a mine's supply curve will be vertical and it will stop producing (i.e., the cost of producing the next unit is essentially infinite, as shown on Figure 3-1). While this modeling choice is often used, the assumptions that it relies on, as well as its limitations, are not often explained. We attempt here to provide some insights into these aspects of this traditional approach.

- First, it is important to stress that assuming that the supply curve is flat up to a certain point is not straightforward. Appendix A addresses the question of



(a) Short-term supply curve for an individual actor in a competitive market.



(b) Aggregate supply curves for multiple suppliers, showing the traditional “stair-step” approach.

Figure 3-1: The aggregation of short-term supply curves resulting in a “stair-step” curve, as described by Tilton (1992, pages 53 and 55 respectively).

why the first part of the cost curve can be considered as flat when calculating supply at a timescale that is not instantaneous. Nevertheless, it is important to acknowledge that this approach is a simplification and does not reproduce *actual* cost curves.

- Moreover, limitations arise when assuming that an individual cost curve becomes vertical after a certain point, since this assumption means that increased prices do not lead to an increased supply. While supply cannot be infinite and there are capacity constraints, it is important to account for potential additional production — whose costs would increase sharply. Indeed, it would become increasingly expensive to yield each additional unit when producing over the optimal rated capacity, for instance using overtime labor, etc.
- Finally, representing the total supply curve without adapting it to the level of demand may be confusing. Simply drawing the curve and inferring the price where supply meets demand, suggests that we can observe *in reality* the suppliers whose costs are above the market clearing price. However, such an assumption is unrealistic since firms whose operating costs are above the price will — almost always — not actually operate. In effect, the supply curve components above the market clearing price essentially present, at best, a prospective supply curve.

3.1.3 Considerations about Market Clearing

Economic theory assumes that market-clearing will occur, and in particular that the aggregate supply will meet the aggregate demand at each period. The actual mechanism that takes place to ensure this market clearing, as well as the way one can implement it in a market model, are questions that are not often addressed in common studies¹.

A characteristic of markets is that actors cannot fully coordinate at each period; for practicality reasons first, since it would be extremely hard to gather all producers or alternatively all consumers to achieve such a coordination. Another reason is due to the very regulation of markets: suppliers are not allowed to collude and fix a collaborative price, nor are groups of consumers allowed to form cartels.

Tackling the issue of market clearing in market models, while incorporating both economic theory and the reality of the market, hence becomes challenging. The **M:5** model has been built to address this issue of market clearing by using the notion of a “market-maker” — as observed for precious metals for instance — that mediates trades between consumers and suppliers, and computes the “fair” price considering the balance of current material offers and supplies. While this mechanism usually takes place on a daily basis with instantaneous supply and demand values, the model assumes that, on a quarterly basis, the market-maker can infer the aggregate “real” supply and demand curves, and fix a resulting price. Section 3.2.2 will address this notion in more details.

3.2 Description of the Model

The **M:5** model has been implemented as a spreadsheet model in Microsoft Excel® for flexibility and transparency. For the purpose of simplifying this stage of model development, demand is treated as exogenous, although there is no structural limitation to incorporating a full-blown demand model in the future. In order to add a certain degree of price responsiveness to simulated demand, these “exogenous” demands can be made price sensitive by setting a non-zero price elasticity in the model inputs for a particular consumption sector. With demand trends and a set of inputs describing sources of supply (i.e., mines, their production economics, and their production

¹There is however a formal domain, referred to as the study of the “microstructure” of a market, that studies these mechanisms. As acknowledged by Cohen et al. (1981), this field has been initiated by the work of Stigler (1964) and the term itself has been later introduced by Garman (1976).

capacities), the model can simulate market clearing over time, calculating a market-clearing supply and price at each period.

Figure 3-2 shows the basic architecture of the model. This schematic representation of the model identifies the main components of the model. “Candidate suppliers” and demand are model inputs, and the other components are calculated simulation model results.

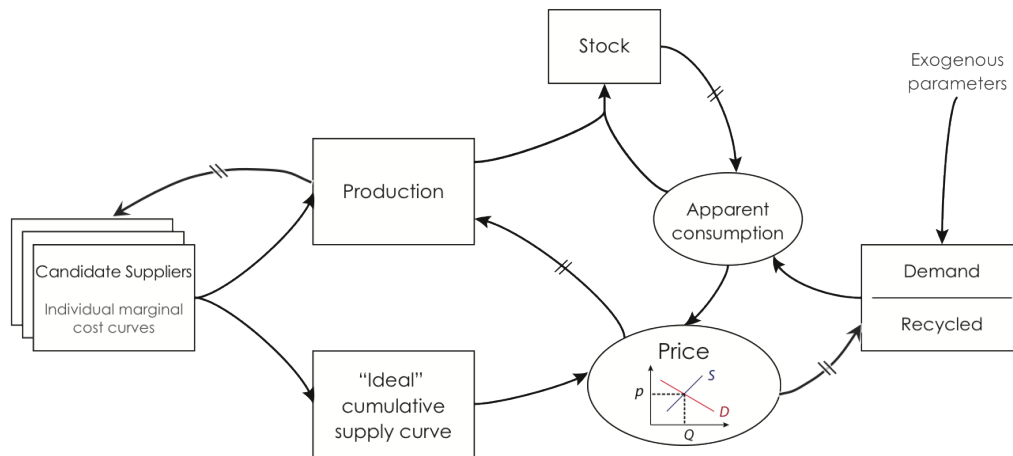


Figure 3-2: **Overall architecture of the model.** The arrows are an indication that one component influences the behavior of another. For instance, there is an arrow linking the “candidate suppliers” and “production” to indicate that the individual cost curves of suppliers contribute to the calculation of the production. Moreover, two slashes on an arrow indicate that the impact the unit has on its “target” is delayed in time — for example, the model assumes that price influences the next period’s production, as we will mention later.

The next sections will describe in greater detail what each of those model parts comprise.

3.2.1 Description of Suppliers and Construction of Supply Curves

Most of the inputs required to run the model describe the suppliers. Specifically, a list of the current mines has to be provided, as well as their respective cost structure. With these data, the available production can be described as precisely as possible within the confines of the modeling assumptions, while using data that can be obtainable from financial reports or that can be derived by observation and intuition.

Using these data, a total industry supply curve is constructed that reflects the behavior of profit-maximizing firms having the characteristics given in the inputs. The

functional form for all supply curves derives from an assumption that the marginal cost is always increasing with Q . In particular, the average cost curve has a polynomial second derivative of the form (see Appendix B for details of the derivation):

$$\frac{\partial^2 AC}{\partial Q^2} = a \cdot Q^n$$

Instead of a “conventional” step function, assuming infinite marginal cost above maximum rated output, we have chosen to approach the question of supply curves by including the notion of marginal cost curve when the production is greater than the optimal operating point (*i.e.* the minimum of the average cost, Q^*) and, given the assumption that the second derivative of the average cost is positive, each unit produced in excess of Q^* costs more on the margin. The modeled shape of the individual supply curves is thus a flat line up to the minimum of the average curve, and then follows the shape of the marginal cost curve until the ultimate production capacity of the mine of the period, as explicated in Appendix A.

This behavior is presented in Figure 3-3. In this figure, producer 1 (the red curve) is able to produce up to a certain quantity at the lowest cost (represented by a horizontal line) and, beyond that threshold, the cost of production becomes a steep curve — namely the marginal cost curve — that is interrupted at the maximum production capacity of the supplier for that period (symbolized by the star on the figure).

In order to account for the fact that market players have incomplete information and, in particular, the fact that a supplier may not be able to base its quarterly production on a perfect knowledge of other suppliers, the model is built using the assumption that the amount of information used for the decision-making is limited to (a) each supplier’s production curve and (b) the price of the material in the preceding time period. Since suppliers always try to stay in business and not make a negative profit, the rationale for this assumption is that each actor produces as much as is economically feasible until the cost of extraction reaches the price of the last period, as illustrated in Figure 3-3.

Assuming that suppliers will simply not produce at all if the price is below their minimum average cost is, however, an overly strong simplifying assumption. Moreover, it seems unreasonable that a mine would stop producing after having opened if the price is slightly below its operating level. Instead, the model allows already open mines to operate at a loss, accumulating that loss up to a cap at which point the mine simply closes. The rate at which the production declines is estimated at each period, depending on the difference between the price and the operating cost. If prices go

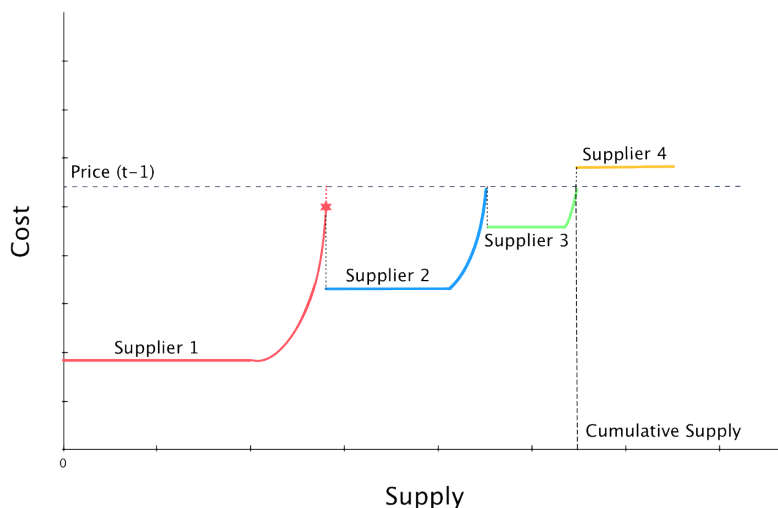


Figure 3-3: An example of aggregated supply curve. Each supplier produces up until the previous price, or their physical capacity for the period considered.

up again and the mine is still operating, production will also ramp up progressively, following a comparable pattern. Appendix C fully describes this specific case.

The model also assumes that new mines will open, but a new mine can enter only when the market price stays above the entering mine’s projected operating cost for at least 3 full years before it begins producing.

Production is calculated for each operating mine at each period. There are several possible conditions under which a mine might choose to produce and, to simulate this behavior, the model implements different mechanisms that are — to the best of our knowledge — reasonable in the sense that they incorporate the notion of incomplete information as well as some real-world observations about openings and closings of mines. These implementation choices, fully described in Appendix C, include:

- The “standard” production decision-making of open mines whose operating costs are below current price and hence maximize their profit by producing up to their physical capacity or the price level
- The establishing of delays in mine openings, coupled with a monitoring of price levels to influence the decision of opening the mine on “economic feasibility” grounds
- The allowing of production at a cost higher than current price when mines are already open, since an immediate shut-down would be unrealistic. There is hence a monitoring of financial losses with a fixed cap.
- The establishment of a progressive ramp-up or ramp-down in production when the price is below the minimum operating cost, with an exponential factor that

adapts to price levels

The question then arises of how the model determines a market-clearing price, since production is decided independently by each supplier and is hence not strictly coordinated, as we mentioned earlier. The next section will describe how we tackled price-setting as well as demand in our model.

3.2.2 Price-Setting Mechanism and Demand

Price-Setting

While the model simulates the reality of incomplete information by assuming that suppliers do not base their production decisions on a perfect knowledge of the other market actors, mines still provide annual financial statements that include information about production costs. Hence, the model assumes that market clearance occurs through the actions of a simulated market-maker that gathers financial information of all producers in order to set the price where the “ideal” supply meets the anticipated demand. This “ideal” price is the price at which the output of each rational producer sums to meet current demand, where each rational producer would only produce until his operating cost equals that of the next supplier. This concept is illustrated on the Figure 3-4.

When demand intersects the ideal supply curve on a marginal cost curve (as shown on the Figure 3-4), the market-clearing price is computed as the resulting marginal cost. However, if the demand curve intersects the supply curve on one of the curve’s ‘flat’ segments, a true market maker would not set the market clearing price equal to the indicated production cost, because this region of the supply curve is a convenient fiction, as explained in Appendix A. Instead, when demand intersects the supply curve on a step, the model computes the price according to whether or not the ideal supply of the “cut-off” supplier exceeded demand. The modeled market-maker selects a cost-based price that encourages a lower discrepancy between supply and demand in the following year, as detailed in Appendix C. Finally, the calculated price is averaged with its previous value in order to limit significant — and possibly unrealistic — price excursions.

Demand

As indicated in preceding sections, the model treats demand as exogenously defined, with consumption distributed across several market segments, each having its own

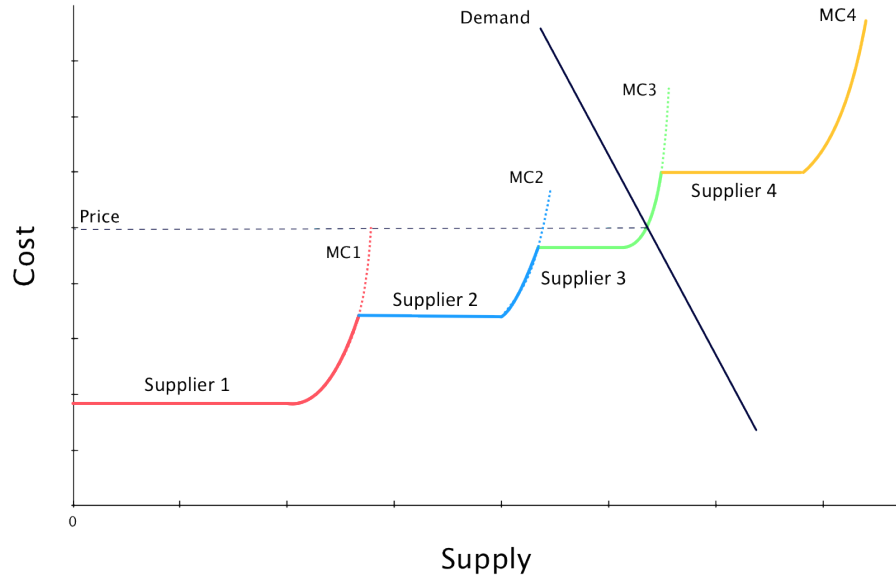


Figure 3-4: The price is set by the market-maker where the demand meets the “ideal” supply curve.

annual growth rate.

In order to consider the effects of differential responses to price excursions across these segments, each consumption sector can be assigned a characteristic price elasticity, which imparts a limited price responsiveness to the overall sectorial growth in each period. Appendix D will describe in greater detail how we accounted for elasticity.

The functional form of the supply curves — in particular the stability convention leading to their “flat part” — combined with both incompleteness of information and limited demand sensitivity, inevitably results in a discrepancy between supply and demand, which the model treats by the creation of a stock. The next section describes how stock is handled, as well as how mines evolve dynamically.

3.2.3 Stock and Mine Dynamics

Because of incomplete information and constraints on coordination, suppliers tend to produce a quantity that may not be strategically optimal to match demand. In particular, a profit-maximizing firm will operate at the output level where its marginal cost of production equals the market price, instead of stopping where their cost reaches the level of the next supplier. When the production exceeds its “ideal” level (indicated on Figure 3-4) we assign the resulting production imbalance to a running stock in the

model. The model seeks to avoid stock accumulation during the following period by assigning the oversupply from the preceding period to a virtual “supplier” that has a lower operating cost than all primary producers. This computation choice might be changed in the future, but satisfies both our simplicity requirement and empirical evidence.

In addition to running individual stocks for each producer, the cumulative production is monitored to account for mine expansion and ore grade degradation. A first order estimation approach to ore grade degradation was developed. This degradation results in the ‘expansion’ of the mine, and in particular in the evolution of the optimal production quantity as well as the concomitant increase in operating costs, as explained in Appendix E.

Now that we have laid the theoretical grounds of the model, it is interesting to evaluate how the **M:5** model differs from existing modeling approaches to materials’ availability.

3.3 Presentation of Existing Modeling Approaches and Comparison with the M:5 Model

Materials availability has long been the subject of study in the field of environmental economics, and many models have been built to explore the question of scarcity and market volatility. This section reviews the different approaches that exist, namely economic abstraction, econometrics and financial modeling as well as simulation tools.

3.3.1 Analytical Modeling Using Economic Abstraction

The work of Hotelling (1931) has been the origin of many research works on the economics of materials exhaustion. From this theory and its developments have resulted different modeling approaches, grounded in an economic abstraction of the behavior of non-renewable resources markets.

Presentation of the General Economic Approach

The following rule has been derived from the work of Harold Hotelling: the market price that leads to the socially efficient rate of extraction of an exhaustible resource is

the price that ensures that a producer's rent (*i.e.* the difference between the market price and the marginal extraction cost) increases at the social discount rate. This social discount rate is often assumed to be a market interest rate. The rule derives from the observation that, for an exhaustible resource, there is an opportunity cost to a firm extracting a material at any point in time, since the potential profits of selling it at a later time are foregone. The private actor, in the case of perfect competition, will hence be indifferent when the “scarcity” rent of extraction, which is total marginal cost (or market price) minus the marginal cost of extraction, is increasing at a rate equal to the current interest rate for a potential investment of the money obtained when selling the material.

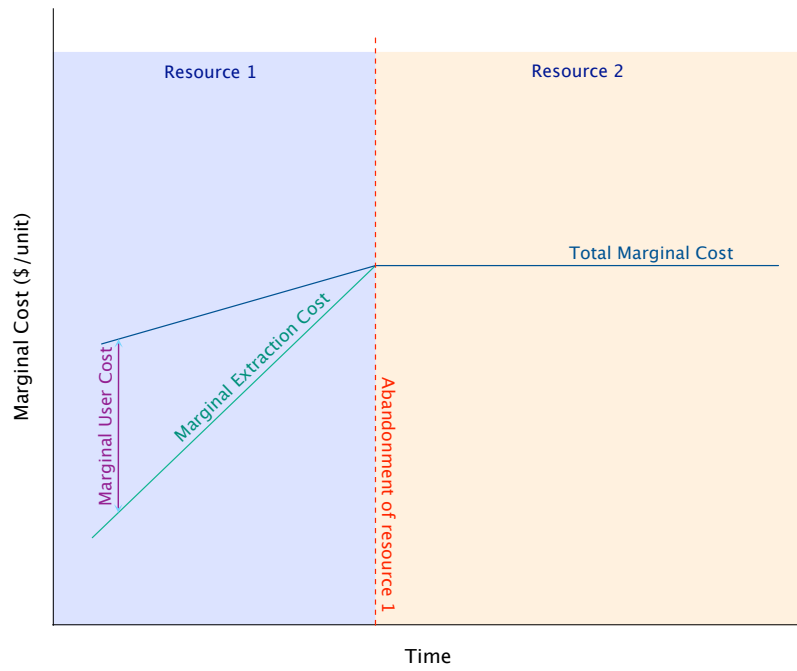
Subsequent work has added to Hotelling's original approach to the economics of exhaustible resources by considering exploration and reserve uncertainty (Pindyck 1978), technological development (Solow 1956), as well as increasing marginal extraction cost and materials substitutability (Dasgupta and Heal 1974). In their article, Devarajan and Fisher (1981) review the major developments in the field, emanating from Hotelling's work.

An interesting result that comes from such an approach is that when the marginal cost of extraction increases, the *marginal user cost* or *scarcity rent* of the material decreases until the total marginal cost of extracting the material reaches that of a substitute. At that point, it is not dynamically efficient to produce the first material, and its exploitation is abandoned for the benefit of the substitute (ideally a renewable resource) — there is hence no real *exhaustion* but rather an abandonment of the resource (Dasgupta and Heal 1974). This concept is illustrated on Figure 3-5 where both the evolution of marginal costs and extraction are represented.

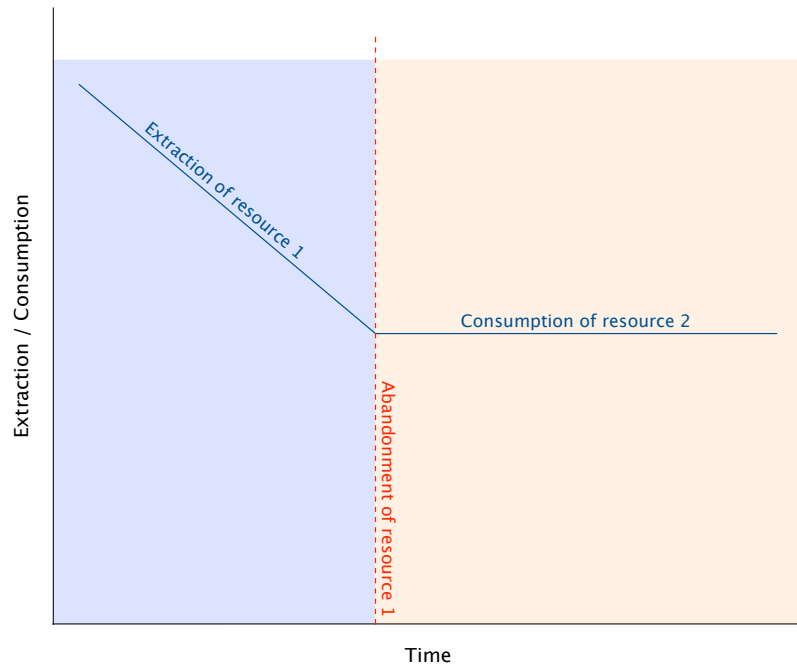
Limitations of the Approach

Such approaches however present several limitations.

Perhaps one of the most important ones — considering the scope of this work — is the fact that it takes an abstract economic point-of-view, looking at the question of material availability with the lens of the market as a whole and economic efficiency from a macroeconomic perspective. As a result, a manufacturer will not be able to use such an approach to make a short-term decision about a material, since the notion of individual firm and individual impact of exhaustion is not really studied. Rather, the approach of Hotelling and his intellectual inheritors is a long-term consideration



(a) Evolution of the marginal costs with time, when switching from resource 1 (non-renewable) to resource 2 (renewable).



(b) Evolution of extraction and consumption with time, when switching from resource 1 (non-renewable) to resource 2 (renewable).

Figure 3-5: The case of a non-renewable resource with an increasing marginal cost of extraction, based on the theory developed by Dasgupta and Heal (1974).

based on “socially optimal extraction”, the “known” reserves for the material, and the aggregate marginal extraction cost.

Other limitations come from the adopted idealized vision of the market. While authors such as Hotelling do consider the case of monopolies, other market imperfections — incompleteness of information, exogenous disruptive events like conflicts or strikes, externalities, poorly defined property rights etc. — are not usually explicitly considered, which results in an assessment that does not encompass the whole picture of the market. While it is interesting to develop this type of approach in order to frame theories about non-renewable resources, it is less relevant for a manufacturer that needs a criticality-assessment in the short-term that considers as many criticality sources as possible, in particular market imperfections.

Comparison of Such Approaches with the **M:5** Model

The **M:5** model as described in Section 3.1 differs from economic abstraction approaches by providing a tool that focuses decisions and strategies at the firm-level, both on the supply-side and on the demand-side of the materials markets. Moreover, the timescale considered is significantly different, since the abstract economics approaches described above tend to focus on the long run, whereas the model developed during this work emphasizes the short-term — while still incorporating medium- to long-term considerations such as depletion and mine expansions.

The **M:5** model is also shaped to be used by an individual decision-maker that can refine the outputs of the model by implementing different demand scenarios; conversely, approaches grounded on an economic abstraction of markets consider the market as a whole and not the specific events leading to the abandonment of a resource, but rather its inevitableness because of aggregate cost and finite crustal abundance. This focus derives from the desire to develop a tool that informs individual firm decision-making, which is both short-term and typically contingent upon an uncertain future.

The construction of the short-term supply curves in the **M:5** model *has* been grounded in standard economic theory, since much of the behavior of individual mines can be treated through conventional microeconomic arguments about profit maximizing behavior, particularly the way in which pricing signals influence production decisions.

3.3.2 Financial-Based Modeling Approaches

The financial modeling-based approach is one that is often used by consulting firms and some manufacturers. Instead of reliance upon economic theory to frame the model, it employs econometric regressions of financial data to infer future demand and supply.

Presentation of the Financial Models

Mines prepare annual financial reports to present their operating results — including their annual production and their operating cost — which is the main source of data for financial models. Assuming that firm production decisions are based upon cash flow recovery, these econometric models aggregate the known capacities of existing and prospective mines, ordering them from lowest to highest operation cost to generate an industry supply curve. Then, using demand forecasts, these models set the price level using the estimated industry supply curve to find where the level of industry output fulfills forecast demand.

The timeframe considered in these approaches is very short, usually spanning from one to four years. Supply and demand data are gathered on a yearly or bi-annual basis. Usually, a regression of either supply or demand is then run on different parameters — and in particular market price. The equilibrium point of price and output is then inferred from the other curve, so that forecasted supply can meet this consumption target. It is hence a short-term approach.

These financial models are particularly useful in revealing price cycles and trends, as well as the effect of exploration or technological changes on markets, by studying historical data and inferring relevant drivers and parameters (Labys, Lesourd, and Badillo 1998).

Limitations of the Approach

Financial-based models present several limitations that are different from those cited previously for models based on economic abstraction.

On the one hand, they are largely grounded in financial reporting data, evaluating demand on the one hand and supply on the other. This approach gets around the so-called “identification problem” (Koopmans 1949) when using regression to model supply and demand, since there is nothing in the historical data that can distinguish between the two — there is, in effect, only one observation than can be made which is

simultaneously demand *and* supply. The regression approach, therefore, usually relies on the very important assumption that supply and demand can be independently determined and ignores potential interactions and dynamics². In particular, demand is calculated based on historical trends of given parameters, independently from the question of price levels or supply constraints.

On the other hand, a regression model fundamentally assumes that the future will be similar to the past. Hence, structural changes in the market deriving for instance from technological discovery, restructuring of consumer demand, or fundamental income effects, are not formally accounted for in the model, unless specifically treated in the formulation — which requires technical insights that most financially-focused analysts are unlikely to have. The short-term aspect of such assessments thus provides good insight when a decision needs to be made very quickly, but this limits the visibility for a manufacturer that would like to study different scenarios and have a better sense of medium-term market behaviors. An example would be that of a firm that is planning on launching a new technology and would need the 10 to 15 years projection of the market in order to verify whether the supply for the required material is sufficiently well established to sustain a mass development of the technology, or not. The insights a financial model would provide in such a case would not incorporate either the “disruptive” aspect of the demand pattern or the longer-term effect of this increase in demand.

Finally, the scope of the projections can sometimes be more tuned towards supply actors, and in particular the decision for price is based on the financial data of the different mines. Moreover, the way in which regression on demand is performed depends on the modeler’s choice. In particular, demand aggregation for the different demand sectors can be done either prior to any regression, hence what is considered is the total ‘consumption’ for the material; or regression can be performed for each sector independently and then the curves aggregated. While the second case may provide manufacturers with useful insight so as to how specific structural characteristics of demand may influence the market, it can be much harder to identify which sector has a structural impact in the first case. Hence, from a manufacturer perspective, it can be challenging to extract sector-level information to inform better decisions, while the fact that different sectors can behave differently can actually have a very significant impact on the market, as will be discussed later in Section 4.2.2.

²There are very sophisticated techniques that are used to solve this issue — such as regression models of simultaneous equations (see, for instance, Kmenta and Gilbert 1968) — but their complexity tends to limit their applicability in the real world.

Comparison of Such Approaches with the **M:5** Model

In essence, a financial model will be similar to the modeling approach that has been adopted in this work, since they both can be characterized as supply-demand models. In particular, the price is set at a level high enough to enable the last producer to operate at a “reasonable” cost — namely at a cost that allows him to recover his total cost.

Several aspects of financial models differ from this work’s approach, however. The first one is that the timeframes within which the models work are different, since the **M:5** model aims at projecting supply and price sufficiently far out in time — about 15 years — so that manufacturers can get a better picture of the market evolution and make better-informed design and production decisions.

Another conceptual difference between the two approaches is that financial models do not account for the interactions between supply and demand, nor do they adjust demand to price levels and supply evolutions. Conversely, the supply-demand **M:5** model has been built so that demand would be sensitive to price evolutions, and hence indirectly to supply. The supply-demand interaction is also implemented in the **M:5** model via the establishment of a stock, arising when there is a discrepancy between supply and demand levels, and affecting the price by changing the shape of the supply curve.

Hence the **M:5** model is similar in essence to financial models, but adopts the point of view of an individual firm or demand sector in order to devise demand decisions that are sustainable on the current market.

3.3.3 Simulation Tools: the Example of System Dynamics Modeling

Finally, different types of simulation tools have been developed to look at materials availability with a dynamics perspective. These methods, and in particular system dynamics models, are very comprehensive in that they aim at representing a complex system by using a system of interdependent non-linear first order differential equations. These systems are reduced to difference equations, which are then used as the basis for simulation models that develop system behavior for a variety of initial and operating conditions.

Presentation of System Dynamics Models

System dynamics models are particularly efficient when it comes to modeling the behavior of inhomogeneous actors, as well as implementing time delays. The notion of *feedback* is also of great importance, and such models work with influence relationships between systems — for instance for recycling as a secondary supply stream. In particular, Alonso from the Materials Systems Laboratory at MIT developed a system dynamics model for the platinum market (Alonso 2010) showing that changes in recycling rates, resulting either from market forces or extra-market policies, can significantly influence market prices in materials markets subject to supply pressures. The work by Urbance of the Materials Systems Laboratory (Urbance 2001; Urbance et al. 2002) used a systems dynamics model to study the responsiveness of the magnesium supply chain to changes in automotive demand. The study revealed the dominant influence of barriers to entry — deriving from the technical and economic structure of the magnesium die casting industry — upon the expansion potential for the structural magnesium market overall.

The price-setting mechanism in the model by Alonso (2010), as well as other system dynamics models, is driven by *inventory coverage*. More specifically, it is assumed that a market-maker ensures liquidity on the market by selling and buying from an inventory in order to set the price at the level where the producers willingness-to-accept is equal to the consumers willingness-to-pay. More specifically, the pricing mechanism formally examines the size of this inventory coverage, and adjusts prices according to the simulated level of coverage as compared to a targeted level of coverage.

Limitations of the Approach

System dynamics models are often very thorough in their description of the market — a large amount of data is collected in order to describe as accurately as possible the behavior of each individual actor in the market. As a result, the resources required to gather enough data for such a model are extremely large. In many cases, it could take several person-years of effort to gather enough information about supply, demand, recycling and speculation in order to accurately describe the market for one given material. Such an approach is incredibly time- and resource-intensive and cannot always be used by manufacturers that need a quick assessment of market behavior for several materials. While it provides great insights on the market as a whole and enables the user to keep track of the different flows over time, the amount of effort required to build it and have it running is very large.

Moreover, system dynamics models frequently rely on modeling ‘fictions’ that are elaborated by the model creator, such as the notion of “inventory coverage”, or measures of “willingness of an actor to make a specific decision”. Such fictions are not grounded in reality and, while proxies can be developed, have no real either physical or analytical analog. Hence, a third-party user might treat the model as a “black-box” tool, which lessens its effectiveness. A model that instead relies on available and reported data as well as uses generally-accepted theoretical constructs in a transparent manner, offers a better understanding of its operations and, thus, of its results.

Comparison of Such Approaches with the Model Presented

When building the **M:5** model, the intent was to implement a sufficient amount of information about the market so as to accurately capture structural characteristics, while keeping it sufficiently simple and flexible in order for a manufacturer to easily switch from one material to another, and run insightful analyses without spending too many resources to do so.

The **M:5** model hence differs from system dynamics approaches by using a less data-intensive approach to materials markets; the downside of such an approach is that it inherently reduces the accuracy of the modeling by limiting the amount of precision put into the model. Instead of requiring a full description of all the actors on the market, the **M:5** model only requires a list of suppliers with some financial data in order to describe the supply curve, but the latter has the same functional form for each actor, even though it is parametrizable. However, this loss of accuracy is an implementation-specific design feature. If the analyst wants to increase the resolution power of the **M:5** model, it is possible to do so by simply expanding its implementation through increased data. On the other hand, this design flexibility cannot be found in system dynamics model, since the calculations are not transparent. For instance, there is no data that can reveal “inventory coverage” or other pseudo-metrics used by modelers to describe actions.

Another difference in the system dynamics approach is the way inventory is considered. In the case of system dynamics models, inventory is what ultimately sets the price, using the rationale that, if the inventory is too low, the price should increase to provide a sufficient incentive for producers to enter the market and produce more, and vice versa. In the supply-demand model developed for this work however, inventory is merely an instrument for managing period-to-period imbalances in supply and demand, and is not the dominant factor in setting the market clearing price.

While system dynamics models are very thorough and powerful tools that comprehensively capture the complexity of materials markets and model the dynamic interactions between supply, demand and price, they require a very detailed description of all the individual components of the market that are endogenous to the model. As a result, the data and resources required are too high to be gathered in a timely fashion for many different materials, putting real limits on the ability of an individual firm to make strategic decisions across a broad spectrum of materials.

This section reviewed the existing modeling methods that tackle the question of materials availability. The supply-demand model that has been developed is aimed at tackling the gaps we have identified in this section, and at providing a simple and generalizable tool, easily parametrizable by a manufacturer and requiring few inputs, yet still capturing the notion of market dynamics and imperfections. The following section will detail the different trade-offs that have been made when constructing the **M:5** model, in order to reach the desired level of precision while limiting the effort required to reach it.

3.4 Specifics of the M:5 Model and Applicability

This section presents the specifics about how a user can use the **M:5** model to customize it for the materials market of interest, as well as to assess alternative demand scenarios and policy strategies. While Section 3.1 describes the theory behind the **M:5** model, here we demonstrate how it can be used in practice, as well as present the type of question it can or cannot answer given its limitations and assumptions.

3.4.1 A User “Manual” for the M:5 Model

This section presents the different actions a user can perform with the model, in order to implement different scenarios and compare their relative impact on the market. In particular, it describes what can be specified in the user inputs and how structural changes in the market — whether in the demand or the supply side — can be translated into parameter changes in the model.

Interface with the Supply Side

In the **M:5** model, the list of suppliers — described using a limited set of financial data at the desired starting point of the simulation — is defined as an input. It is this list that makes the model specific to a given material market, since it describes the current (and possibly expected) market players.

While the general shape of the supply curve is set by modeling assumptions based on economic theory and a desire to limit the amount of information needed to run the model, the actual parameters of the supply curve may be specified by the user.

The inputs required to describe a supplier are listed below, and fully described in Appendices A, B and E:

- Q_i^* , the *initial* optimal production quantity. It is the quantity that the mine should be producing at a given period, in order to operate at its lowest average cost.
- A_i^* , the *initial* minimum average cost of production. It is the point where the average cost curve and the marginal cost curve cross, and the resulting production is Q_i^* .
- a , the multiplicative factor of the second derivative of the average cost function. It is a scaling factor.
- n , the polynomial exponent of the second derivative of the average cost curve. It is possible to change it to affect the steepness of the marginal cost curve — hence allowing for more or less supply above the “optimal” production point, as explained in Section 3.2. Adjustments to this parameter could be used, for instance, to compare the effect of a more or a less stringent environmental mining regulation: the steeper the curve, the more stringent the policy (i.e., a steeper curve indicates that it gets increasingly more expensive to produce each additional unit).
- f_1 and f_2 , the two interpolation parameters to invert the marginal cost curve. While they are mainly calculation parameters, f_2 also is the multiplicative factor of Q^* that is the upper limit of production at each period. For instance, if $f_2 = 2$, then the mine cannot produce more than $2 \cdot Q^*$ at each period — due to physical and operational constraints.
- α , the rate of decline of the ore grade. The higher it is, the more quickly the ore grade will degrade when the cumulative production increases.
- g_i and g_{min} , the initial and minimum ore grades, respectively. In particular, g_{min} constitutes the ore grade floor, in the sense that a lower ore grade would not be economically profitable to exploit for the mine.
- K_{tot} , the expected total cumulative output of the mine. It is the ‘reserve’ of

- resource that investors project when opening the mine.
- τ_{life} , the projected lifetime of the mine, as established by the investors when opening the mine — it is used to allocate the investment costs over time.
- χ , the capital invested initially in the mine, discounted for its expected lifetime.

Because **M:5** is a spreadsheet model, the user can easily access the individual calculations made to simulate supply and other outputs for each time period. As a result, the user can implement a “supply disruption” scenario, where, without impairing the overall behavior of the model, the user can choose to let a given mine either stop producing for a given number of periods, or produce only a fixed amount for a given period of time (simulating a quota).

Finally, the **M:5** model can be used to simulate the opening of new mines. If potential new actors are described on the inputs page, the model will add them to the list of suppliers if the price is high enough that they can feasibly operate. The model, of course, considers that there will be a delay in the opening of a new mine, reflecting the influence of risk aversion on the part of the new mine operator. If these conditions are satisfied, the model will incorporate this new mine into the market supply, and offers a assessment of the effect this additional supply source may have on the market.

Changes in Demand

One of the design choices made when building this modeling tool was to have demand exogenously defined. While a notion of feedback has been implemented via the use of price elasticity of demand, the underlying demand trend is defined by exogenous parameters — such as the growth rate and the price elasticity of each sector. Hence the user of the model has the ability to refine a demand scenario and evaluate the consequences of the different parameters on the simulation results.

A user can choose to have the demand calculated at each period following the functional form described in Appendix D. As constructed in the model, total demand has been segmented into different sectors that can be independently described. By providing a growth rate, a seasonal factor, a price elasticity, and the demand segment’s relative share of the global demand at the initial point in time, a manufacturer can describe an existing market and use growth forecasts for each sector in order to see the impact of such a scenario on the existing market. Additionally, recycling has been implemented in the **M:5** model as an exogenous mechanism whose occurrence is specific to each demand sector, characterized by the recovery rate and the average lifetime of products within each sector.

Demand can also be described fully exogenously by using a direct forecast and using this externally estimated scenario as a time series executed by the model. This operating mode is particularly useful when a decision-maker has already developed a specific demand scenario and wants to see its impact on the market. This feature exists so as to allow for more sophisticated demand scenarios, since the current implementation of demand is fairly simplistic.

Other Actionable Levers

Besides direct interactions with the list of suppliers and the different demand sectors' parameters, the **M:5** model offers other parametrizable calculation tools. These features have been implemented for transparency and flexibility — the model makes some general assumptions about markets, but offers the possibility to change these assumptions.

Opening and Closing of Mines: As described in Appendix C, the model allows for mines to operate at a loss, since it would not be realistic to completely shut down the mine on the sole ground that the price just went below the minimum operating cost of the mine. The moving financial loss is monitored over a period of time that can be set by the user, and the overall loss acceptable before the complete shut-down of the facility is also a modeling parameter. Moreover, production ramps up and down according to an exponential factor τ (defined in Appendix C), whose evolution, given the cumulative loss, can also be tuned by the user. As a component of the model's simulation of the “opening” of a new mine, the length of the period during which the price should be above the projected operating cost of a new mine can also be set by the user.

Price Elasticity of Demand: Appendix D describes how price elasticity of demand is used to implement the notion of supply-demand feedback. Because this calculation depends upon a weighted average of past prices, the user can incorporate additional refinement to each demand sector's price sensitivity, by changing both the weights of the moving average and its length.

Price-Setting and Production: The assumptions governing the behavior of the market-maker can be modified by the user — in particular, the values used to adjust the price level if there is an under- or an over-supply can be changed. Moreover, while the production calculation currently allows producers to extract up to the minimum of *(a)* the price of the previous period or *(b)* their ultimate

physical capacity at that period, that decision-making can be changed by using, for instance, an *expected* price value. While these calculations are not fully parametrized yet, they are easily accessible.

3.4.2 Assumptions and Resulting Simplifications of the M:5 Model

This section presents the different simplifications that have been adopted during the implementation of the model.

Exploration and Discovery

The current version of the M:5 model is deterministic. In particular, the list of suppliers — current and projected — is set by the user. A mechanism has been devised so that the entrance of a new actor on the market is delayed in time and grounded in the rationale that the operating and investment costs are recovered over a reasonable timeframe. While the decision of opening the mine is based on the price level, it is deterministic in that only the listed suppliers may be in the market.

In reality, the market for non-renewable resources presents uncertainty, especially when it comes to discovery. In his paper, Pindyck (1978) introduces the notion that the reserve base is variable. The M:5 model incorporates an idea of exploration, in that each mine evolves with respect to its cumulative production; specifically *(a)* the ore grade degrades at a certain rate (set by the user), *(b)* the production increases with time while *(c)* the cost of extraction slightly increases as well, but this process is deterministic.

The scope of the model is to address the short- to medium-term question of whether a demand scenario is sustainable given the current supply sources. Because a stochastic discovery and exploration process introduces considerable complexity, these features were not implemented in this version of the model. However, future work on the model could incorporate the question of variability in discovery of new mines and expansion of existing ones.

The Question of Stock and Investment

One of the main assumptions of the M:5 model lies in the way material stocks have been implemented. In M:5, stocks are a bookkeeping instrument to account for

oversupply or undersupply in any time period. When stocks are nonzero, the value of the stock is currently treated as an additional supplier having the lowest cost of all operating suppliers so that the stock accumulated at one period will be consumed in the next period. As a result, stock as it is handled for now affects the price by shifting the supply curve “to the right”, increasing the available supply on the market and possibly lowering the price of the resource — conversely, an undersupply leads to an increase in price.

In reality, a more strategic handling of stocks takes place in the market. On the one hand, manufacturers may have an incentive to keep a certain level of inventory as a buffer to hedge against demand when prices for feedstocks are excessive. Similarly, producers themselves might keep a positive level of inventory that they can use to manage variable or seasonal demand — it hence becomes a safety buffer. In the current version of the model, this “running stock” is held constant for each actor, and it is not elastic to price levels.

Another aspect of stock is its influence on the behavior of a third class of actors in the resource market, that of investors or speculators. In markets like precious metals, the high stakes and material values lead to the involvement of outside actors — such as investors — that are neither direct consumers nor suppliers. By buying stock at low prices and selling it when prices increase, these speculative investors add an additional complexity to the market and influence price levels by acting either as consumers or producers, depending on price levels.

Such behaviors will have an impact on price levels, and can either result in exacerbated price excursions, or conversely in a reduced price volatility. For simplification reasons, and in order to limit the amount of necessary input data, the current model can only implement these behaviors in a limited fashion. Indeed, a demand sector can be created with an upward-sloping demand curve (*i.e.* a positive price elasticity). Yet this approach does not capture the full scope of an investor’s behavior and further modeling efforts could be oriented towards implementing it in greater detail.

The Handling of Recycling

A related modeling simplification is that **M:5** implements recycling as both exogenous and deterministic. a recovery rate and an average product lifetime are modeling input parameters for each sector. The quantity recycled at each period is then determined as a fixed percentage of the demand at time $t_i = t - \text{product lifetime}$. This approach assumes that both the recovery rate and the product lifetime are certain, hence making

the recycling stream deterministic. The quantity recycled at each period is then added to the stock value and gets consumed at the next period.

A more realistic perspective on recycling could incorporate uncertainty both concerning the rate and the lifetime of the products. Since recycling is determined by demand sector, the model could be improved by using probabilistic distributions around the average values for recycling, rendering this simulation of the secondary stream stochastic, in closer accord with reality.

As was the case for stock, the amount of material that gets recycled at each period may be held so as to get sold when the prices are higher. Similarly, higher prices on the market may encourage a higher recycling rate. Hence, incorporating price sensitivity when calculating the quantity of material recycled and sold may add some additional realism in the model and make the estimate of price at each period more accurate.

Yet, even with these limitations, recycling still has an impact on the overall stability of the market, as we will see in Section 4.1.3.

3.4.3 What Types of Questions Can the M:5 Model Answer?

Based on the description of the model that has been given in Section 3.2 and on the model assumptions and limitations listed in the previous paragraphs, this section provides insights so as to what type of questions can be treated by the **M:5** model and the insights that can be gained from the use of such a model.

First, it is important to note that the model that has been developed does not have a *predictive* purpose, but rather is a tool that enables the user to compare different scenarios, evaluate their relative impact, and act on different market-level levers. Rather than giving exact values for future prices and supply, the model aims at warning the decision-maker when there is a risk with a large potential impact, from the point of view of the manufacturer. It can hence be seen as a tool that *(a)* flags excessive risks and *(b)* compares the relative impacts different scenarios and policies can have on the market and on a manufacturer in particular.

In the rest of this section, we will provide some sample questions the model can answer, considering its foundations and limitations, and given the actionable levers that have been mentioned in Section 3.4.1.

Questions Relative to Supply

The **M:5** model offers a great flexibility in the characterization of the suppliers. As a result, several types of questions can be addressed via the use of the model. Some examples are provided below.

Influence of Supply Structure: By changing the distribution of suppliers — the concentration of supply, as well as the distribution of cost levels — the user can compare the relative impact of different structural characteristics that can reflect real-world observations of evolutions of supply sources. Moreover, the effects of mine openings or closings can be explored.

Impact of Supply Instability By imposing supply values for particular suppliers over a given period of time (for instance, forcing a supplier to not produce for number of years), the decision-maker can study the effect of such a disruption on the price and the behavior of the market in the longer-term. When looking at critical elements, supply disruptions may occur due to external events — conflicts, strikes, governmental strategies, etc. If there is an expected risk of such supply disruption, it is possible for a manufacturer to see its relative impact on the market and hence help him devise a better-informed strategies in the face of these risks.

Effect of Mine Dynamics By allowing mines to expand with respect to their cumulative production and the resulting depletion of the ore grade, the user can analyze the relative impact of mine maturation and aging has on the longer-term supply for the material, since it depends on the actual production.

Questions Relative to Demand

By treating the demand as exogenous, the **M:5** model allows for a large flexibility in the implementation of demand scenarios. Several types of questions can hence be asked by a manufacture or a policy-maker; some are listed below:

Influence of Demand Structure Launching a new technology that uses a significant amount of a given material means either creating a new demand sector, or increasing the demand of an existing sector. In both cases, projecting the resulting expected demand in the **M:5** model will enable a decision-maker to evaluate whether the current state of supply can sustain the increase in demand or to project the point in time when demand becomes unsustainable.

Impact of Demand Instability As was the case for supply, critical materials markets can be subject to instability on the demand side. Because of the often constrained supply, some demand sectors may decide to abandon the material for a substitute. The model offers the possibility to simulate the impact of such a disruption on the market.

Effect of Price Elasticity Another type of question that the model can address is that of the impact price sensitivity of a demand sector on the market. While an individual manufacturer may have a very clear sense of his particular price sensitivity of demand, what really drives price fluctuations in the face of supply disruptions is the collective sensitivity of the overall market. By decomposing price elasticity according to end-use sector, **m:5** enables the analyst to explore the implications of price sensitivity differences by sector, with particular emphasis on how marketshare interacts with this parameter.

Questions Relative to Other Types of Policies

Finally, several levers have been implemented to compare the effects of different policies on the market, including public policies.

The Role of Recycling: While precious metals' markets have a well-established secondary stream with an efficient recycling process, it is not the case for all materials. It can hence be interesting to evaluate the impact of the introduction of, or changes to a secondary stream upon the market, especially when facing a high demand or an unstable primary supply.

The Effect of Policies Specific to a Material: There are a variety of situations in which the market for a specific material may be constrained by public policies that are external to the primary market. One example could be that of the conflict minerals, where the US government discourages the importation of materials from the Democratic Republic of Congo. Another is the case of precious metals: automobile emissions standards have lead to the development and widespread deployment of catalytic converters, and significantly increased the demand for PGMs. The model can address these and similar questions by limiting the number of available suppliers in the first case, or increasing the base demand of the automotive sector in the second case, for instance.

The Impact of Environmental Mining Regulations: While critical materials' markets are not always well-regulated, it can be expected that more stringent mining standards will be imposed in the future. In particular, in the case of REEs, the mining processes in China have put a high stress on the environment, and have recently been more stringently regulated (*Situation and Policies of China's Rare Earth Industry* 2010). By changing the cost curve parameters, and in particular those of the marginal cost of extraction, the model user can address the question of relative impact of the policy on the stability of the market, since it directly implements the policy by changing the cost of extracting each additional unit.

Chapter 4

Results

This chapter presents insights that can be obtained through the use of the model, as well as a discussion of what can be gained from the use of such a model and what the trade-offs are between how much effort has to be applying this type of tool and the improvement it makes. Finally, the model and general observations of critical materials markets are used to provide potential policy strategies to mitigate some types of material criticality.

4.1 Use of the Model to Illustrate Critical Materials' Markets Behaviors

This section presents results that have been obtained with the model to illustrate the behavior of critical materials' markets, and show how the **M:5** model can capture some characteristic dynamics of markets. In particular, the following paragraphs will address the use of **M:5** to explore the structural characteristics of supply and demand, as well as the impact of different policies that have been mentioned in Section 3.4.3.

The inputs used for these analyses are fictional, yet loosely based on real precious metals markets and, in particular, the market for platinum.

4.1.1 Influence of Structural Characteristics of Supply

This section addresses issues of supply structure. Critical minerals markets are frequently supply constrained, as presented in the second chapter of this thesis. It

is hence interesting to model common supply constraints observed on markets and evaluate the overall behavior of the market with the **M:5** model.

The Case of Supply Disruption

In many cases, the supply chains for critical materials have proven to be relatively fragile to operating dislocations. In particular, external events such as conflicts or strikes have impaired the mining operations in a producing country for a certain period of time, often having a dramatic impact on the supply chain and ultimately on manufacturers dependent upon that material. Cobalt is a good example of this dynamic: close to half of the world's cobalt is mined in the Democratic Republic of Congo (DRC)¹. In the 1970's, political unrest in the DRC and Zaire resulted in the temporary interruption of cobalt exports. This restricted supply, combined with increasing cobalt demand and decreasing producer inventories, caused cobalt prices to skyrocket. Though the supply disruption was temporary, the cobalt market suffered: price excursions further nourished labor unrest in Zaire and Zambia, the costs increased and led to source relocations, and manufacturers had to substitute cobalt for alternative materials as well as develop new technologies (Alonso 2010).

The **M:5** model can enable the user to evaluate market's resilience to disruptive events. To illustrate this, the following set of general model parameters has been used.

- The market is moderately concentrated ($\text{HHI} = 20\%$)
- The demand is moderately elastic and grows at a 4% rate
- There is no recycling stream
- The supply disruptions have been implemented as taking place during one year, for both a large supplier (30% of the total supply) and a smaller actor (representing about 12% of the total supply)

The model outputs, namely supply and price, are presented below:

First, the three supply and demand curves on Figure 4-1 illustrate the direct impact of supply disruption: in both Figures 4-1b and 4-1c, a “dip” in the supply is easily observable. In the case of the figure 4-1c in particular, the decrease in supply is more noticeable — since the actor dropping out is larger — and there is a significant impact on the demand (the dotted line) since it is price elastic.

The price evolution shown in Figure 4-2 is particularly interesting. First, it is clear that, in both disruption cases, prices increase due to the sudden undersupply.

¹It is important to note that cobalt is not part of the “conflict materials” as defined by the Dodd-Frank Act, because its mining takes place in a part of the country that is not subject to the same conflicts and hence has not been restrained by the US government.

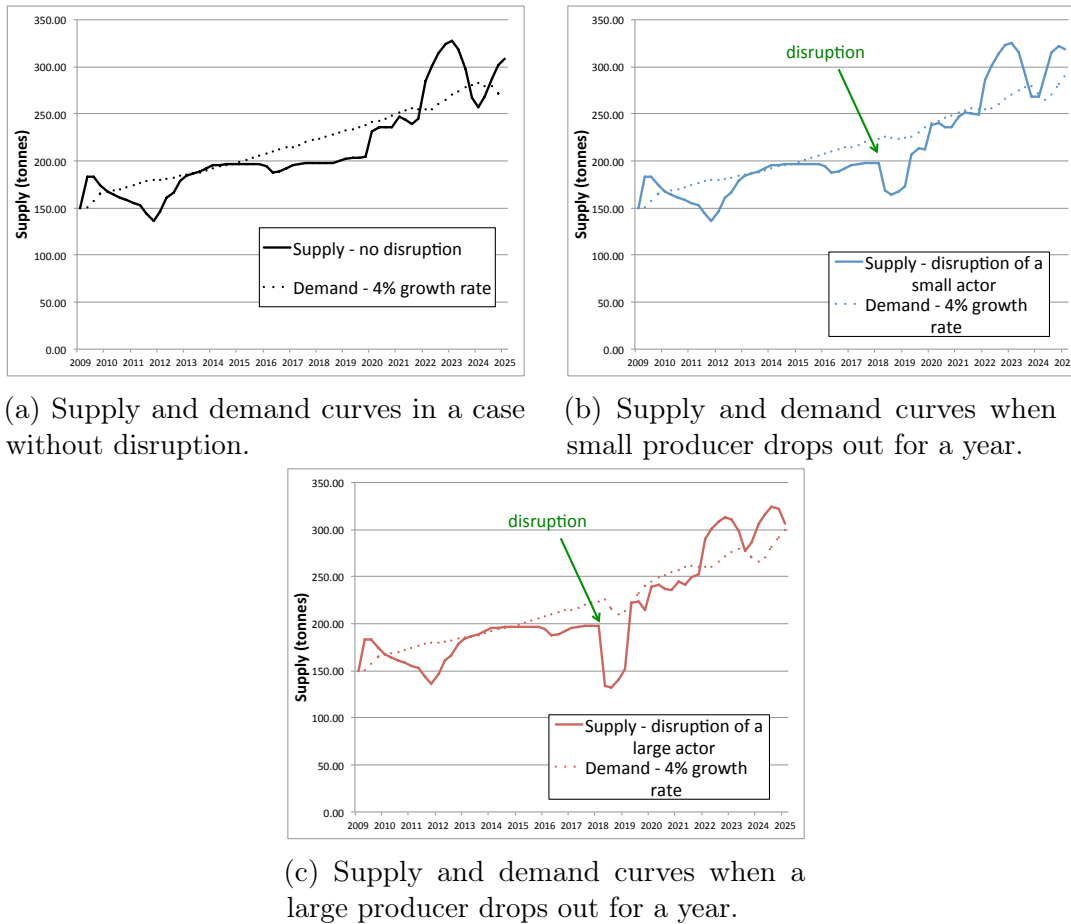


Figure 4-1: The supply and demand curves obtained by the model with a 4% demand growth rate and a moderate elasticity.

The magnitude of the peak, however, is highly dependent on the magnitude of the disruption: a larger actor dropping out leads in this case to a peak about four times as high than when a smaller actor drops out.

The model simulations also tend to exhibit a fairly rapid return to ‘equilibrium’ for both prices and supply, hence suggesting that this market is resilient.

Coming back to critical materials markets, such a result can be extremely interesting for a manufacturer since the vulnerability of the supply chain to disruptions is clear, but can be highly dependent on the supply structure of the market itself. In the cobalt case, Zaire dropping out for a short period of time had a great impact because the relative size of that actor was very large — Zaire and Zambia represented about two-thirds of the global supply at the time (see Alonso 2010, Chapter 3, pp. 45–46). The impact on price was hence very important. The resilience of markets will depend in part on the ability of the demand sectors to cope with the disruptions, which may

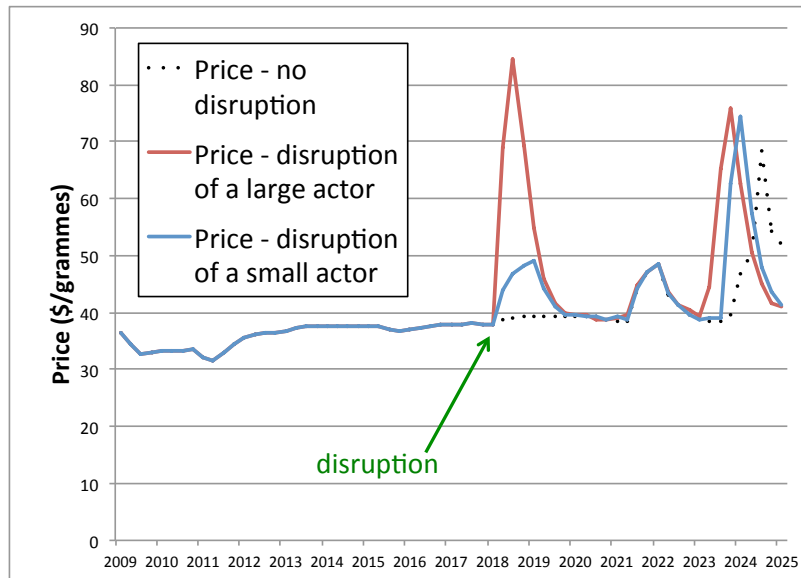


Figure 4-2: Price evolutions resulting from the different supply disruption scenarios, and comparison with the base case of no disruption.

lead to decreased demand — via substitution or technological change — or on potential new entrants on the supply-side that would alleviate the reliance on the unreliable supply source. In the case of cobalt, the crisis resulted in a manifestation of both strategies.

Impact of Entry of New Actors

The mining industry is a particularly cost-intensive industry; as a result, any new entrant will require time to develop confidence that the market price will be high enough to ensure cost recovery, before entering the market. While these delays on the part of the new entrant are understandable, it is less clear how these delays might impact market behavior.

The following analysis explores this question by introducing different degrees of delay on the part of new entrants and couples the analysis with the question of supply cost distribution. In particular, one would expect that the response of the market to entry delay would be related both to the time to become “convinced” and the magnitude of the cost increase the new entrant required. Indeed, there is an interesting question of what type of new entrants are we considering: are they operating at a fairly low cost, comparable to that of already operating mines, or are they on the contrary perhaps smaller and more costly? To tackle this question, the analysis presented here has considered two different types of supply curves, one with lower average cost —

i.e. the majority of the new entrants operate at a cost comparable to that of existing actors — and one where new entrants operate at higher costs, as can be seen on Figure B-1.

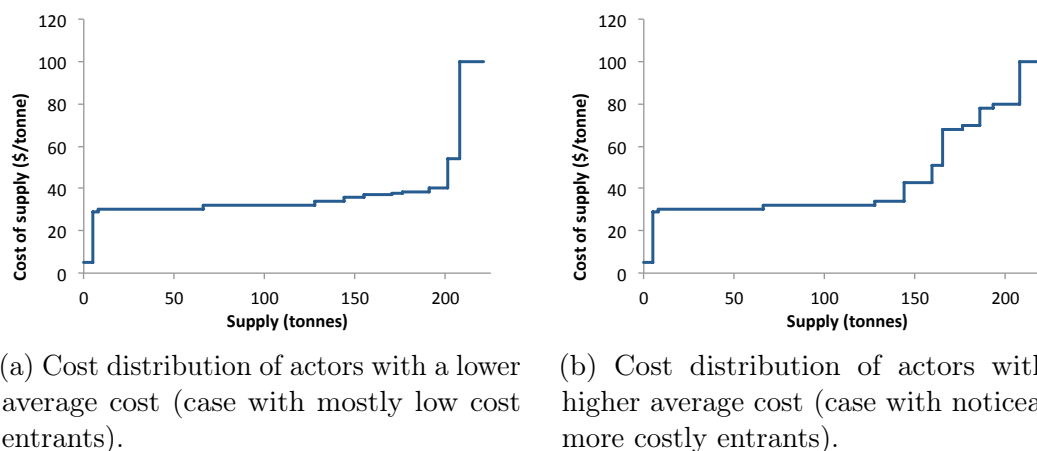


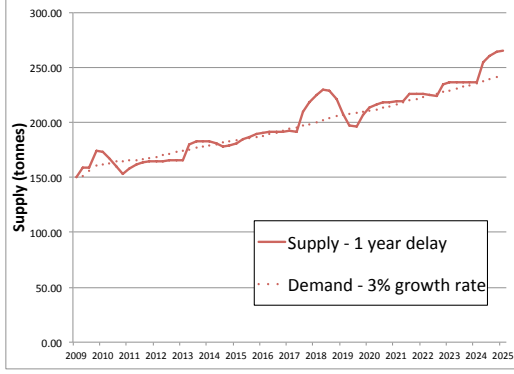
Figure 4-3: Schematic representation of the costs of all the actors — existing and new entrants — that have been used in the analysis.

The analysis itself consisted in changing the required delay during which the price should be high enough to cover total costs, before fully entering the market. Three cases were implemented, one with a one year delay, one with a three years delay (the observed average) and one with a five years delay. The results for both cost distributions are shown below.

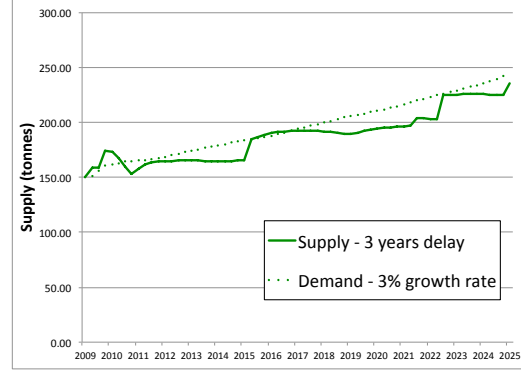
There are several interesting points raised by the simulations depicted above.

First, it is interesting to notice that shorter delays in mine openings lead to a reduced “undersupply”, in the sense that the actual production is more capable of staying in line with the desired demand — represented by the dotted lines — when mines can open more quickly. This illustrates the concept of greater flexibility introduced when mines can make quicker decisions about opening.

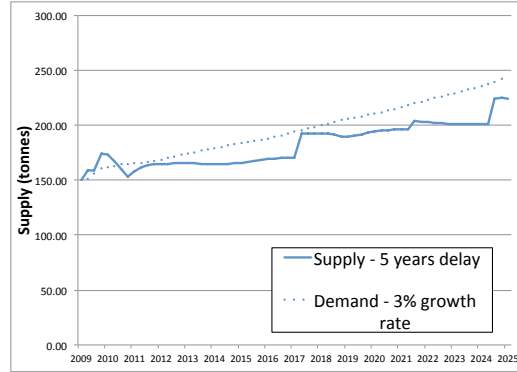
On the other hand, the cost structure has a great influence on the results, as can be seen on Figure 4-6. In particular, when in the case depicted by Figure 4-3b, the price changes are more noticeable, since the new entrants operate at higher costs — hence when there is a short opening delay, prices have a greater volatility because of the differences in costs that lead to greater changes in price. Since a shorter opening delay leads to a quicker entry of new actors, price changes are of greater magnitude. In effect, the simulations at large entry delay times illustrate a new entrant’s rationale



(a) Supply and demand curves with a one year delay before opening.



(b) Supply and demand curves with a three years delay before opening.

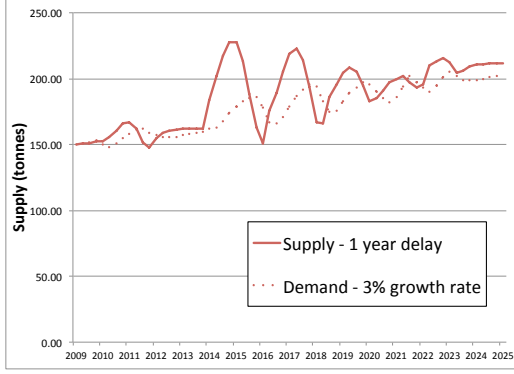


(c) Supply and demand curves with a five years delay before opening.

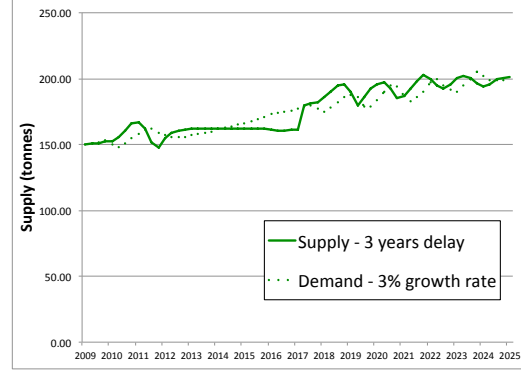
Figure 4-4: The supply and demand curves obtained by the model with a 3% demand growth rate and a moderate elasticity, with the cost structure depicted on Figure 4-3a (mostly low cost entrants case).

for taking a longer time to enter the market. Even in a growing market, a new entrant can find that a too-intemperate entry can actually depress the market price, adversely effecting profitability and, potentially, financial viability of the new mine. A more conservative entry strategy leads to a more stable (and higher) price, and a more reliable cash flow.

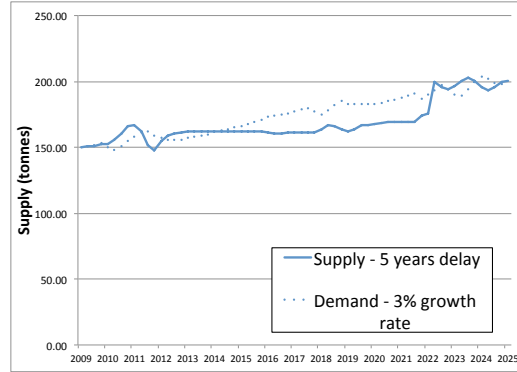
Finally, we can notice that overall price trends do not vary significantly when delays change, especially when the market structure is that depicted on Figure 4-3a. As pointed out in Section 3.4.2, the treatment of stock and the fact that demand is exogenous lead indeed to a less reactive price adjustment when there is an “chronic” undersupply. One could argue that, in reality, prices in the case of longer delay might increase a bit faster due to the fact that the actual production is below the desired consumption — or the driving force of the market. The trends observed, however, are still in line with what we can expect if opening delays were longer, since the increase



(a) Supply and demand curves with a one year delay before opening.



(b) Supply and demand curves with a three years delay before opening.



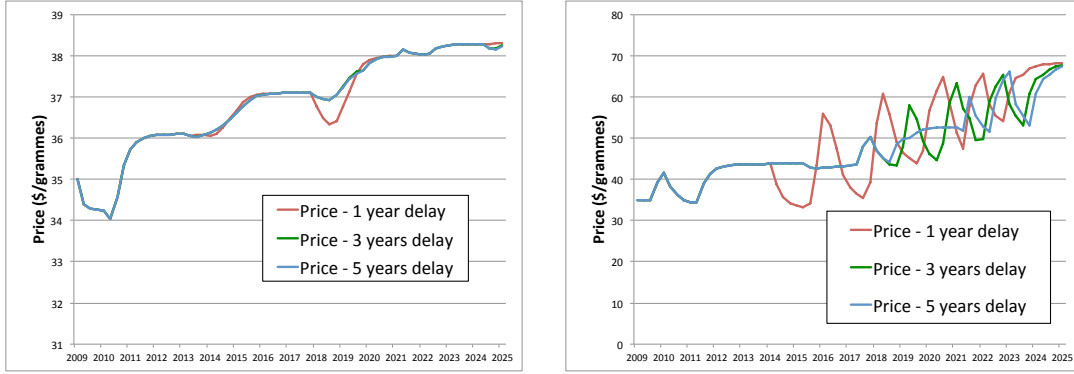
(c) Supply and demand curves with a five years delay before opening.

Figure 4-5: The supply and demand curves obtained by the model with a 3% demand growth rate and a moderate elasticity, with the cost structure depicted on Figure 4-3b (noticeably more costly entrants case).

in price appears more stable, emphasizing the idea that entering too quickly, even in a growing market, tends to increase price volatility. It may hence be more strategic for a new entrant to adopt a more conservative strategy of entry.

4.1.2 Influence of Structural Characteristics of the Demand

When a manufacturer relies on a material, not only is it important to assess the supply reliability, but the relative importance of the sector within the global demand is also an important factor. One can easily imagine that, if a disruptive event such as a price peak or a supply disruption occurs, the impact on a given demand sector will only be greater if that sector represents a large portion of demand.



(a) Price evolutions resulting from the different mine openings scenarios, with the cost structure depicted on Figure 4-3a (mostly low cost entrants case).

(b) Price evolutions resulting from the different mine openings scenarios, with the cost structure depicted on Figure 4-3b (noticeably more costly entrants case).

Figure 4-6: The price evolutions obtained by the model with a 3% demand growth rate and a moderate elasticity, with three different mine opening delays.

Impact of a Demand Sector Leaving the Market

The following analyses have been designed to evaluate the impact on the overall market of a demand sector dropping out.

In particular, two scenarios were implemented: one with a large sector dropping out of the market, hence leading to a larger fall in the demand, and one with a small sector leaving the market.

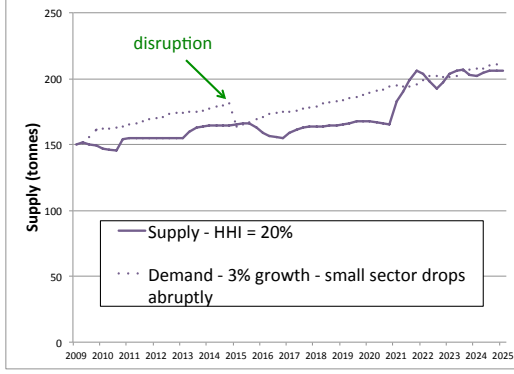
Such circumstances may arise in particular if technological changes take place in a demand sector, leading to material substitution and a shift away from the material — one could think for instance of the case of platinum and automotive manufacturers shifting progressively towards a greater use of palladium as a substitute in catalytic converters — or if new regulatory constraints on imports are put in place.

The conditions of the analysis are the following:

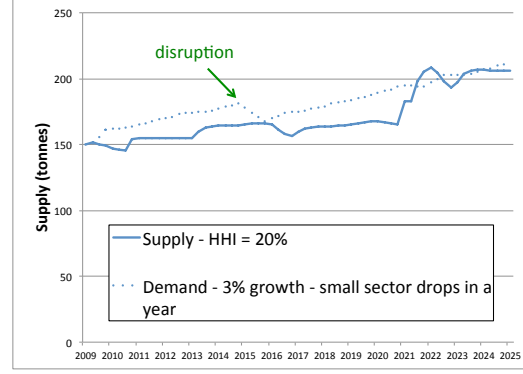
- The market is moderately concentrated ($\text{HHI} = 20\%$)
- The demand is moderately elastic and grows at a 3% rate within each sector
- There is no recycling stream
- The demand disruptions have been implemented as taking place during over a year (hence four quarters) or abruptly over only a quarter.
- The cost structure of the suppliers is that depicted on Figure 4-3a.

Several points are raised by these simulations.

First, the size of the sector leaving the market has a very clear impact, as expected.

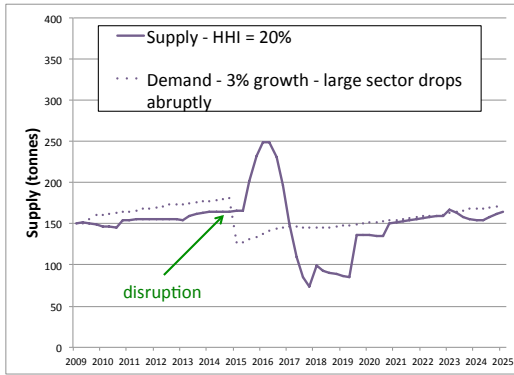


(a) Supply and demand curves with an abrupt drop in demand.

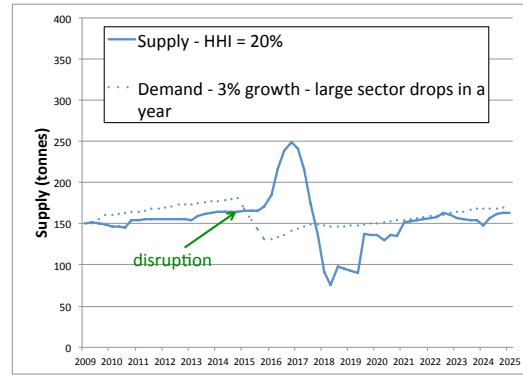


(b) Supply and demand curves with a progressive drop in demand over a year.

Figure 4-7: The supply and demand curves obtained by the model with a 3% demand growth rate and a drop of a small demand sector (10% of global demand).



(a) Supply and demand curves with an abrupt drop in demand.

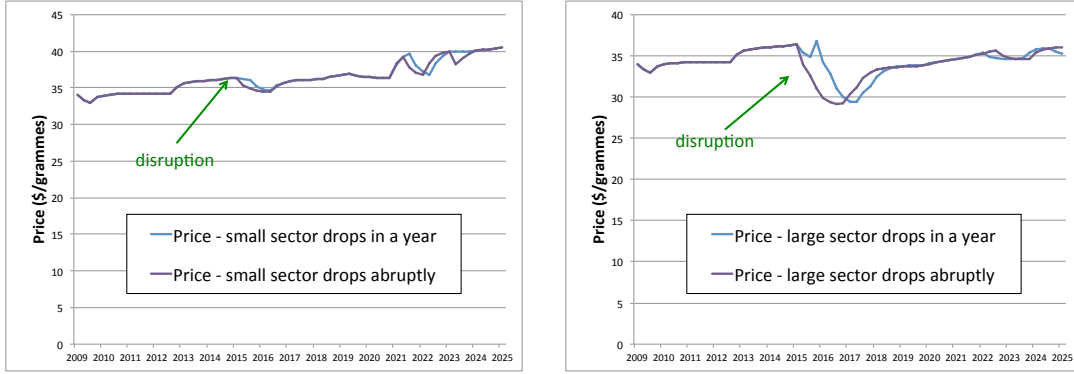


(b) Supply and demand curves with a progressive drop in demand over a year.

Figure 4-8: The supply and demand curves obtained by the model with a 3% demand growth rate and a drop of a large demand sector (30% of global demand).

What is perhaps more interesting is that, in the case of a large sector as shown on Figure 4-8, there is a period with *over*-supply following the drop in demand. This is mainly due to the stock resulting from the sudden fall in demand. Indeed, suppliers cannot react immediately to a fall in demand, partly because of the delay in price adjustment, but also because a mine cannot close immediately and will keep supplying, even if it is at a loss, since the fixed costs are so high.

Then, the prices follow an expected trend that is that they fall very quickly after the drop in demand, hence leading to an ultimate dip in the supply curves that can be observed in particular on Figure 4-8. The prices then ramp progressively back up, in order to give suppliers an incentive to fulfill the orders. Interestingly, when a demand sector drops out, the re-adjustment of the market is more progressive,



(a) Price evolutions when a small demand sector leaves the market.

(b) Price evolutions when a large demand sector leaves the market.

Figure 4-9: The price evolutions obtained by the model with a 3% demand growth rate and a moderate elasticity, when either a large or a small demand sector leaves the market.

since the mechanisms to reduce production and potentially close mines because of over-supply take more time.

Finally, the impact of a more or less abrupt fall in demand is mainly noticeable when looking at prices. Indeed, when the loss in demand is more progressive, the prices tend to decrease slightly more slowly than in the case of an abrupt drop in demand. The impact on supply is less noticeable, but we can still note that, on Figure 4-8b, the supply increases back again a little bit earlier than in the case of an abrupt change in demand.

These simulations are interesting particularly in the case of critical materials, since substitution and technological changes can lead to such situations, where a sector will progressively — or more abruptly — abandon a material to shift to a material that may have a more reliable supply stream for instance.

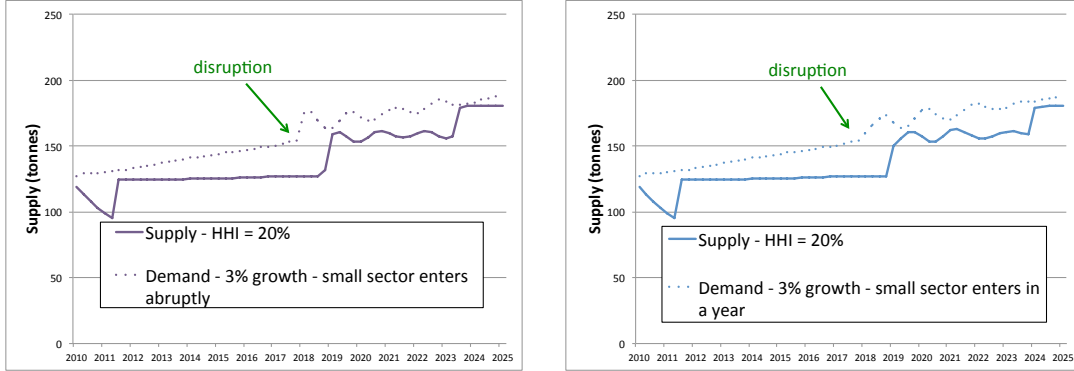
Impact of the Entrance of a New Demand Sector

Conversely, what is the relative impact of a new sector entering the market? Recent technological developments in diverse sectors of the economy are more and more reliant on critical materials, and hence the demand for some materials may diversify in a relatively short period of time.

The following analyses study the case where a new demand sector of moderate elasticity enters the market, and have implemented a case where the sector is a small new player and a case where the new entrant is a large player.

The conditions of the analysis are the following:

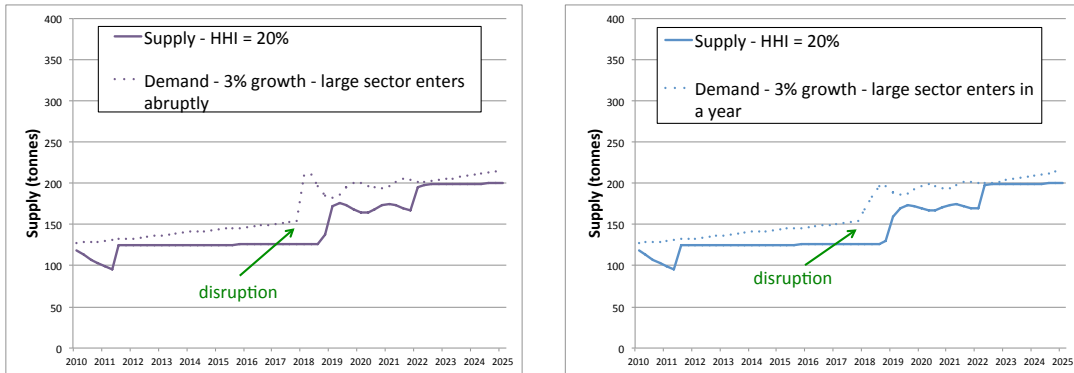
- The market is moderately concentrated ($\text{HHI} = 20\%$)
- The demand is moderately elastic and grows at a 3% rate within each sector
- There is no recycling stream
- The demand disruptions have been implemented as taking place during over a year (hence four quarters) or abruptly over only a quarter.
- The cost structure of the suppliers is that depicted on Figure 4-3b.



(a) Supply and demand curves with the abrupt entry of a new demand sector.

(b) Supply and demand curves with the progressive entry of a new demand sector.

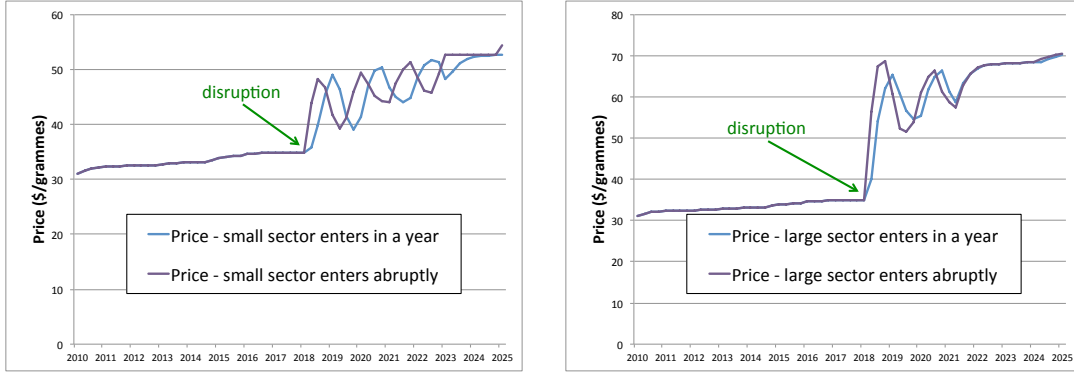
Figure 4-10: The supply and demand curves obtained by the model with a 3% demand growth rate and the entry of a small demand sector (about 10% of the new global demand).



(a) Supply and demand curves with the abrupt entry of a new demand sector.

(b) Supply and demand curves with the progressive entry of a new demand sector.

Figure 4-11: The supply and demand curves obtained by the model with a 3% demand growth rate and the entry of a large demand sector (about 30% of the new global demand).



(a) Price evolutions when a small demand sector enters the market.

(b) Price evolutions when a large demand sector enters the market.

Figure 4-12: The price evolutions obtained by the model with a 3% demand growth rate and a moderate elasticity, when either a large or a small demand sector enters the market.

Several points can be made in the case of a new entrant, with these simulations.

First, there is a clear impact of the entry of a new actor, whether large or small, on price. Indeed, prices rise almost immediately when a new demand sector is created, which can be explained by a sudden undersupply that needs to be fulfilled by new suppliers that are not yet on the market — hence the relative delay in the raise in supply.

An abrupt entry — as opposed to a more “progressive” entry spanning over a year — has the effect of raising prices slightly more quickly. A resulting effect, visible especially on Figure 4-11 when a large sector enters the market, is the impact on demand, since its elasticity leads to a slightly bigger dip following the increase in price when that increase is more abrupt, *i.e.* on Figure 4-11a.

Finally, the magnitude of the impact depends on the size of the new entrant, as could have been expected. The price increase is significantly larger when a large demand sector enters, since it stimulates the production of a significantly larger amount of material.

Critical materials markets have been exposed to similar situations especially these past decades. Indeed, recent developments, particularly in the field of renewable energy, have created new demand on already constrained markets. From these simulations, it is clear that the impact on existing actors is very important, since the prices can increase significantly in a relatively short period of time; such disruptive events on the demand-side can hence be harmful. In particular, since the demand increases, more costly suppliers enter the market, and the increase in price hence becomes durable.

4.1.3 Influence of Different Policy Decisions

Critical materials are important to many different sectors of the economy, but also to actors outside the market. In particular, public and private stakeholders exterior to the primary market may have an incentive to intervene on the market and promulgate policies that will ultimately have an impact on the market itself.

The Impact of Mining Regulation

Mining practices in the case of critical elements can sometimes have a very large impact on the environment and on the labor force. The case of REEs in China illustrates this issue very well, since the excessive mining practices have led to a rapid degradation of the surrounding environment as well as raised issues concerning the workforce.

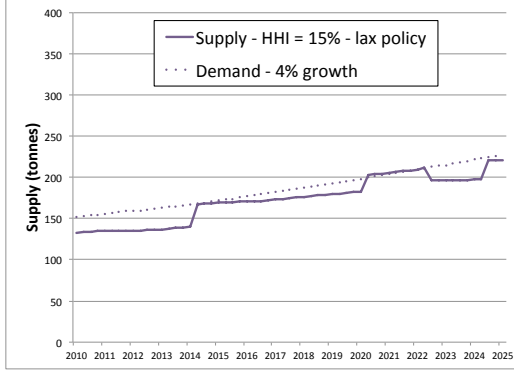
While certain critical minerals' markets are not yet well-regulated, it can reasonably be expected in the future that more stringent regulations be put in place.

Some environmental regulations result in a fixed-value increase in the marginal cost of production; this however only leads to a global raise in the cost structure. What may be more interesting is the case where the energy consumed is regulated — a carbon-tax would have this effect for instance — or overhead labor is more stringently looked at. Then in effect, the change that can be observed is the *steepness* of the marginal cost curve: a more stringent regulation would lead to a steeper marginal cost curve, hence making the production of each additional unit increasingly more expensive.

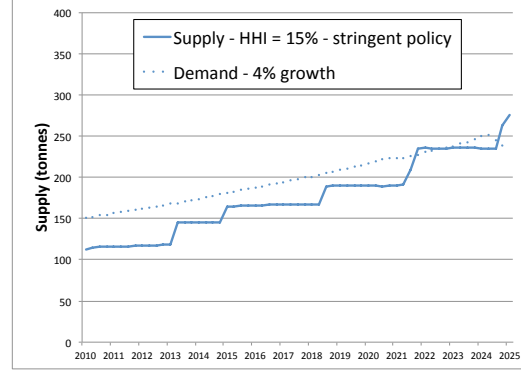
To that end, the following simulation studies the case where a large supplier has a more or less shallow marginal cost curve — as defined by the elasticity of the marginal cost curve at the “optimal” production quantity, and this in three different scenarios where the market is non-concentrated, moderately concentrated and very concentrated, as indicated by the Herfindahl Index.

The conditions of the analysis are the following:

- The market presents three different supply concentration ($HHI = 15\%$, $HHI = 20\%$ and 25%) but the overall amount of material available is equal.
- The demand is moderately elastic and grows at a 4% rate within each sector
- There is no recycling stream
- The marginal cost elasticity in the case of a lax environmental regulation is equal to 1% of that for a stringent policy, for the largest actor.

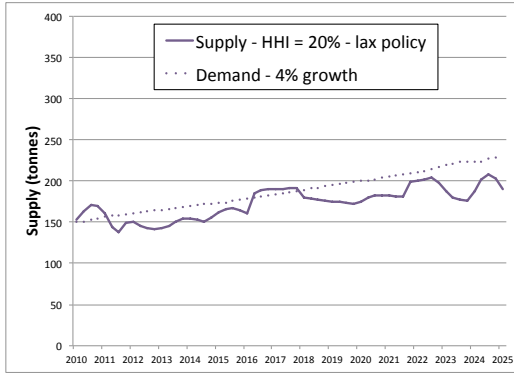


(a) Supply and demand curves with a relatively lax environmental regulation.

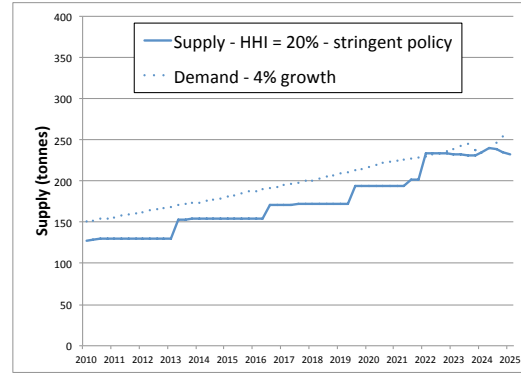


(b) Supply and demand curves with a relatively stringent environmental regulation.

Figure 4-13: The supply and demand curves obtained by the model with a 4% demand growth rate and an non-concentrated market ($\text{HHI} = 15\%$).



(a) Supply and demand curves with a relatively lax environmental regulation.

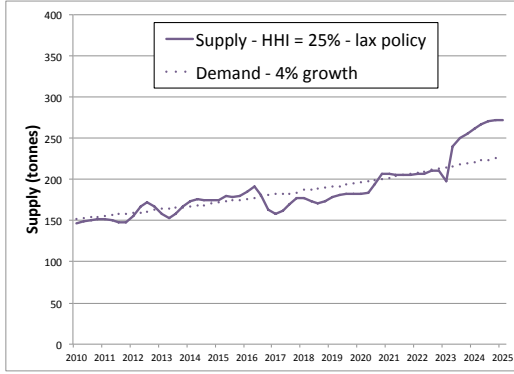


(b) Supply and demand curves with a relatively stringent environmental regulation.

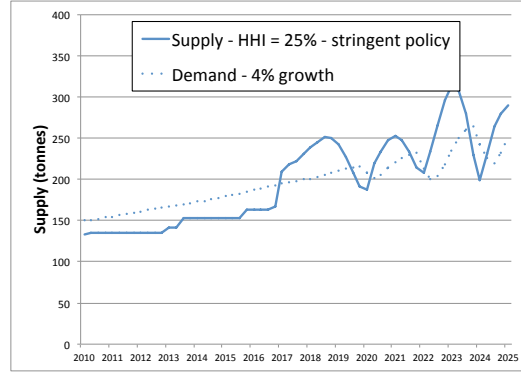
Figure 4-14: The supply and demand curves obtained by the model with a 4% demand growth rate and a moderately concentrated market ($\text{HHI} = 20\%$).

These simulations illustrate the fact that a more stringent regulation will lead to an increase in prices, as can be observed on Figure 4-16.

It is interesting to note that concentration accentuates this phenomenon and amplifies the magnitude of price increases. Moreover, a higher market concentration leading to higher price peaks, the price elasticity of demand leads to large oscillations in price — and in demand, as can be seen especially on Figures 4-14b and 4-15b. A higher market concentration hence increases the volatility of the market, but less stringent regulations for a large actor tend to mitigate the effect of concentration, at least in the medium-term.

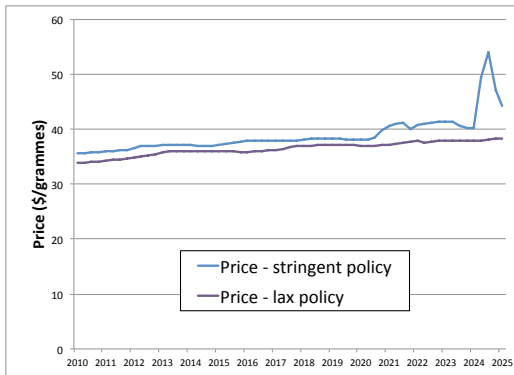


(a) Supply and demand curves with a relatively lax environmental regulation.

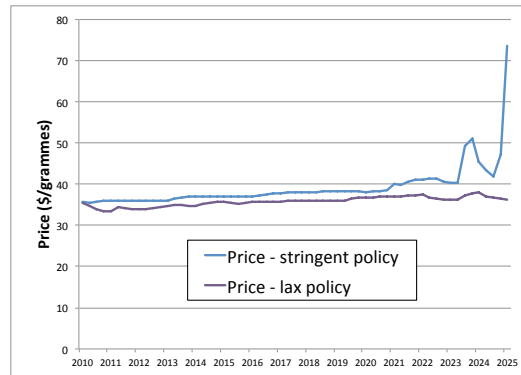


(b) Supply and demand curves with a relatively stringent environmental regulation.

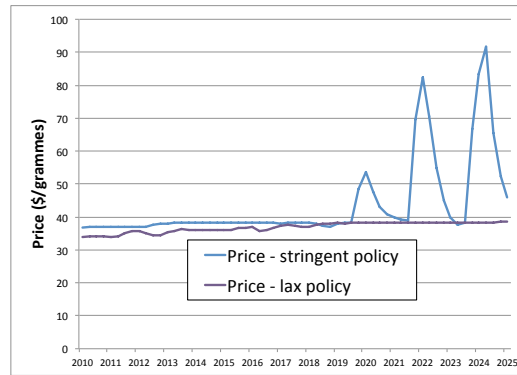
Figure 4-15: The supply and demand curves obtained by the model with a 4% demand growth rate and a concentrated market ($HHI = 25\%$).



(a) Price evolutions for a non-concentrated market.



(b) Price evolutions for a moderately concentrated market.



(c) Price evolutions when a concentrated market.

Figure 4-16: The price evolutions obtained by the model with a 4% demand growth rate and a moderate elasticity, when a large supplier is exposed to a more or less stringent regulation for mining.

The Effect of Recycling

The markets for PGMs are characterized by a well-established recycling stream, in particular within the automotive industry. In her PhD dissertation, Alonso (2010) argues that recycling has a risk-mitigating effect on materials' markets and tends to in particular mitigate price excursions.

This next analysis has been designed to evaluate the relative impact of recycling on a market where there is a supply disruption due to a large actor dropping out of the market for a year — in the same conditions as in Section 4.1.1 above. Here, it has been decided to only affect the recycling rate of the largest demand sector (automotive, in the case of platinum, that represents about 40% of the total demand), knowing that the average lifetime of a product in this sector is of about 15 years. This lifetime has also been modified in one of the analyses to evaluate its relative impact.

The conditions of the analysis are the following:

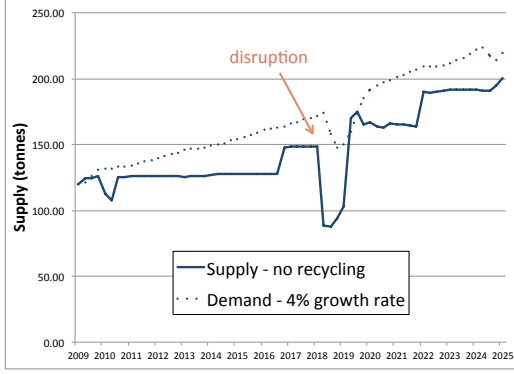
- The market is moderately concentrated ($\text{HHI} = 20\%$).
- The demand varies among sectors, is moderately elastic and grows at a 4% rate within each sector.
- A supply disruption of a year has been implemented, modeling a large supplier (30% of the overall supply) leaving the market momentarily.
- The values 0, 5 and 20% have been used as recycling rates for the largest demand sector.
- The average lifetime of a product within this sector is on average of 15 years, but has been changed to 5 years in the last simulation.

From these simulations can be drawn several interesting insights.

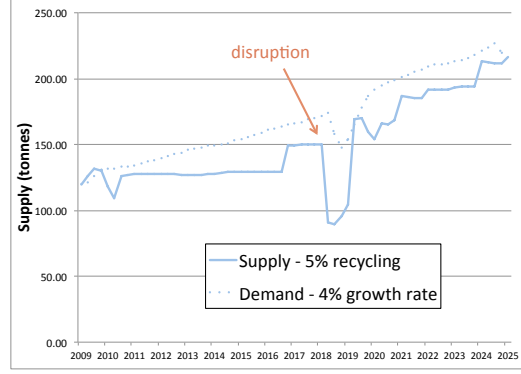
First, it can be noted that recycling does have a mitigating impact on the market, since on Figure 4-18 we can see that, as the rate of recycling increases, the impact of the supply disruption is minimized and the price excursion is not as dramatic. This hence confirms the results proposed by Alonso (2010).

Then, it is interesting to note that a 5% recycling stream does not have a very significant impact on the market when a disruption of this magnitude occurs. This hence illustrates the need for a well-established and efficient recycling stream when facing the possibility of largely disruptive events.

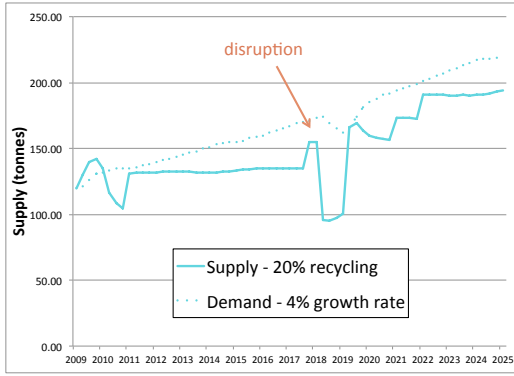
The product lifetime does have an impact on the market — although it is not highly noticeable — since we can see that the prices are slightly lower when there is a shorter lifetime and the supply disruption is somewhat smaller. This can be



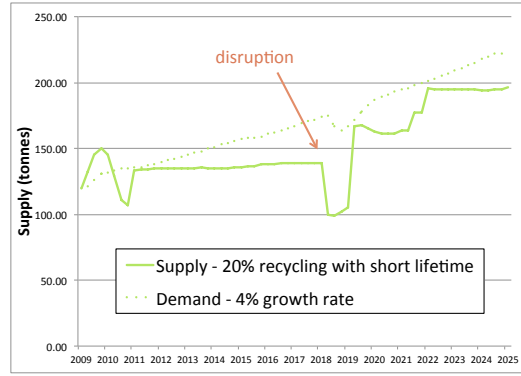
(a) Supply and demand curves with no recycling stream and a 20-year product lifetime.



(b) Supply and demand curves with a 5% recycling rate and a 20-year product lifetime.



(c) Supply and demand curves with a 20% recycling rate and a 20-year product lifetime.



(d) Supply and demand curves with a 20% recycling rate and a 5-year product lifetime.

Figure 4-17: The supply and demand curves obtained by the model with a 4% demand growth rate and a year long supply disruption from a large actor.

explained by the fact that demand is growing, hence 20% of demand 5 years prior to the disruption is higher than 20% of demand 15 years before.

From these analyses, it is clear that an efficient recycling stream mitigates the risks of price excursions, by adding an additional supply stream that is not only dependent on price. It can hence be a policy that manufacturers may want to pursue if the cost of recycling is not prohibitive and the supply is forecasted to present a risk of disruptions.

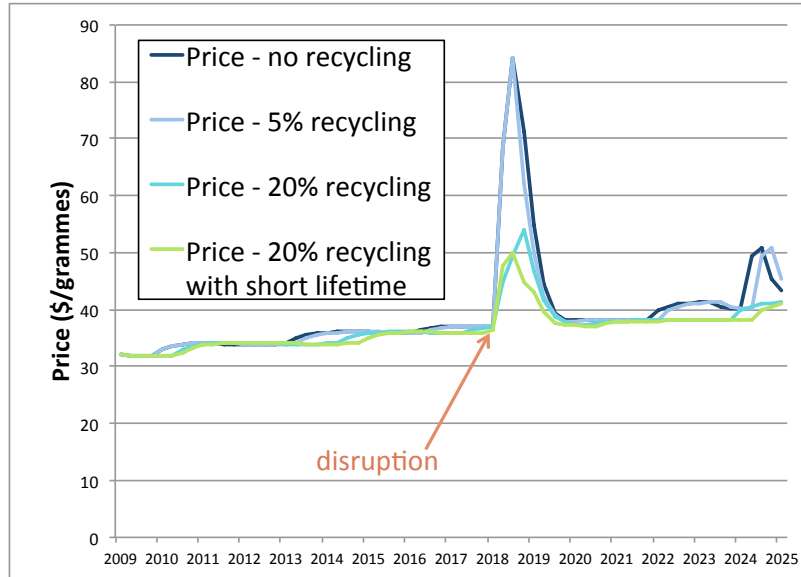


Figure 4-18: Price evolutions resulting from the different recycling scenarios in a supply disruption case.

4.2 What can be Gained from the Model as Opposed to Metrics-Only Approaches

While metrics are often used by manufacturers to make a purchasing decision about a material, they cannot always reflect the market dynamics that have an influence on the market. Hence a metric could indicate a source of concern, but market dynamics and the inclusion of other parameters defining the context may lead to a situation that is not as critical as expected, and vice versa.

This section presents cases where a metrics-based approach can be improved by the use of market dynamics that incorporate feedback relationships between supply, demand and price, and hence provide a more comprehensive insight on the market and the criticality of materials.

4.2.1 The Case of Market Concentration

One of the main sources of worry in the case of critical materials today is the structure of the supply. Indeed, physical constraints and high barriers to entry have led to sometimes highly concentrated markets where the supply lies in the hands of only a few actors that may belong to even fewer private organizations.

A relevant metric to look at when evaluating the risks of supply concentration is

the Herfindahl-Hirschman Index (HHI) that has been defined in Section 2.3.1 of this thesis. This metric is designed to evaluate the relative concentration of the market at a given point in time. It is hence inherently static, and only accounts for the individual suppliers and their relative importance.

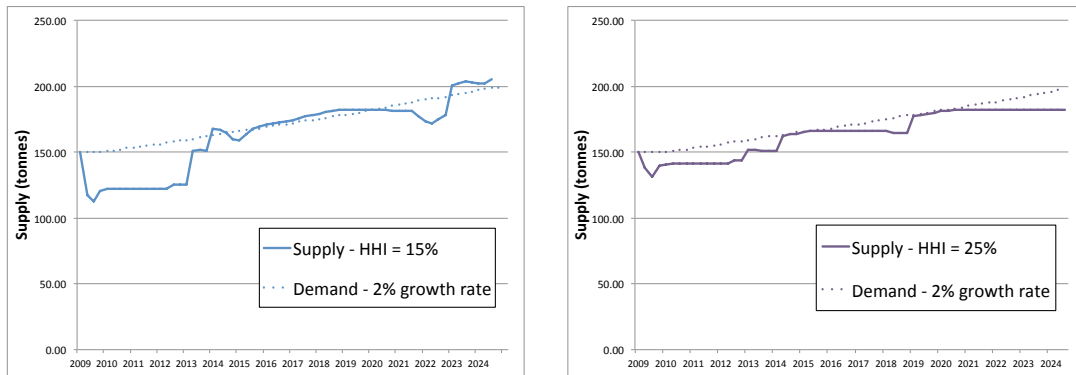
The following analysis compares two markets that overall dispose of the same quantity of material, but have very different supply concentrations as defined by their HHI. Those markets have been constructed by considering a “base” market that is relatively fragmented ($\text{HHI} = 15\%$), and changing the standard production quantities (Q^*) to increase the size of large producers and decrease that of smaller actors. The resulting market can be considered as highly concentrated, with $\text{HHI} = 25\%$. This stylized analysis has been designed to compare the impact market concentration has on a market, and in particular how market concentration interacts with demand growth and leads to more or less ‘critical’ situations.

In order to evaluate the *dynamic* impact of market concentration, two scenarios of demand have been modeled, one with a low growth rate of 2% and one with a high growth rate of 6%.

The general conditions of the analysis are the following:

- The two markets produce the same quantity overall, but have a different HHI at a same point in time.
- The demand is moderately elastic and grows at a 2% and a 6% rates
- There is no recycling stream

The model outputs, namely supply and price, are presented below:



(a) Supply and demand curves in a non-concentrated market.

(b) Supply and demand curves in a concentrated market.

Figure 4-19: The supply and demand curves obtained by the model with a low demand growth rate and two cases of market concentrations.

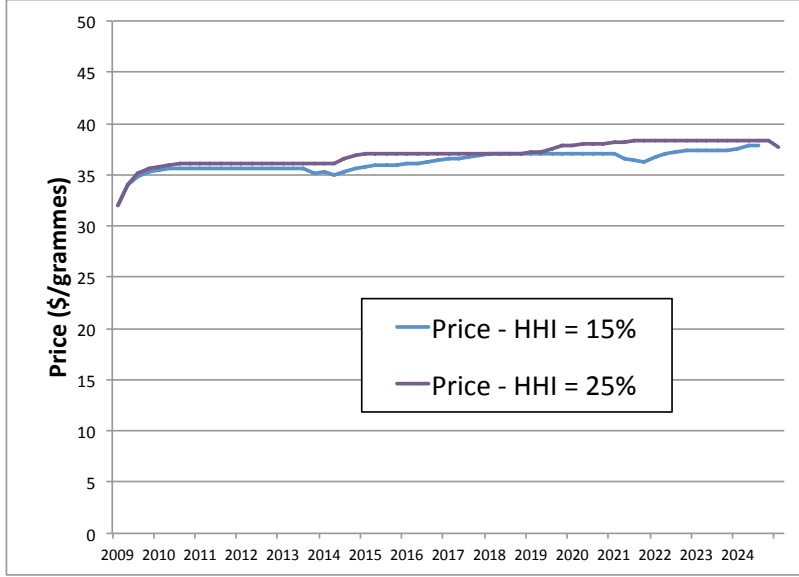
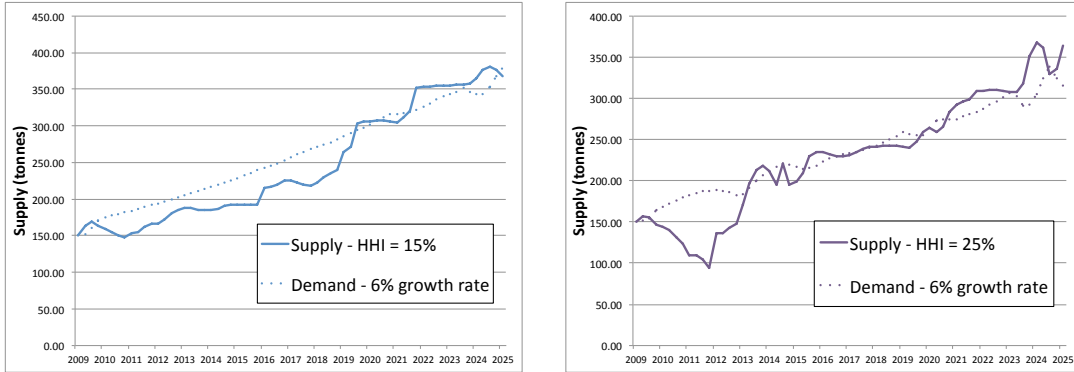


Figure 4-20: Price evolutions with a low demand growth rate, in the case of a non-concentrated market and a highly concentrated market.



(a) Supply and demand curves in a non-concentrated market.

(b) Supply and demand curves in a concentrated market.

Figure 4-21: The supply and demand curves obtained by the model with a high demand growth rate and two cases of market concentrations.

While an HHI value of 25% or over is widely recognized as a sign of high concentration and hence high supply risk, the simulations shown above clearly indicates that it is not always a source of concern and should not systematically discourage a manufacturer to use the material. In particular, several insights can be gained from these analyses.

The first observation that can be made is that, in both cases, a more concentrated market leads to a higher price. This comforts the idea that, in general, a more concentrated supply will lead to a more constrained market and influence the price of

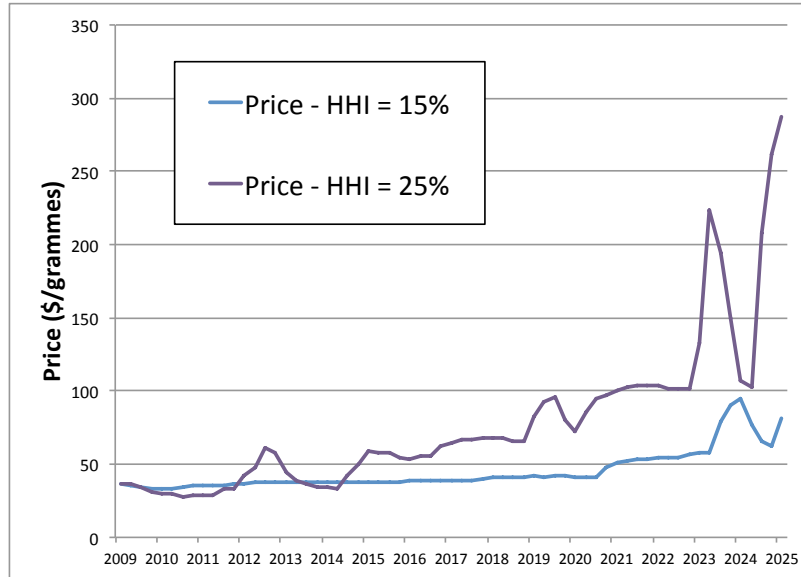


Figure 4-22: Price evolutions with a high demand growth rate, in the case of a non-concentrated market and a highly concentrated market.

the resource, and ultimately impact manufacturers.

The case of a 6% annual demand growth rate strikingly illustrates this risk. Indeed, the price evolution for a highly concentrated market is significantly above that of a non-concentrated market, and more importantly the price volatility is notably larger when $HHI = 25\%$. And that characterizes what a manufacturer may consider as a high risk, since price instability and resulting supply variations can have a great economic impact on a firm that relies on a material and is moderately elastic. Moreover, such short-term instability significantly impairs firms' ability to make decisions about a material, and the uncertainty greatly impairs the planning process, which is a crucial aspect of manufacturing processes. Such results confirm that a high HHI exposes a manufacturer to greater risk.

What is perhaps even more interesting is the fact that, when demand only grows at a 2% annual growth rate in this case, concentration does not really present a high risk anymore. While prices are very slightly higher in the case of a more concentrated market, the overall behavior of the market and the supply do not present disruptive and unstable behaviors; the resulting uncertainty is significantly lower and manufacturers hence do not have to face a risk comparable to that of the high growth rate case.

What can be gained from such an analysis is the fact that, while metrics can be informative from a general point of view, they are not sufficient to properly evaluate the overall behavior of the market, in particular its instability. On the contrary, it appears that, in this case, the *criticality* aspect of the market — namely the

supply concentration — is highly dependent on the demand behavior and on the interactions between supply, demand and price. Those interactions could not be captured by metrics; manufacturers can hence benefit from using a model such as the **M:5** model that offers a more comprehensive assessment of market dynamics and complex interactions, taking into account an array of parameters that can influence market behaviors. The case of growth rate has been chosen in this case, but the impact of market concentration on the market as a whole could also be impacted by factors such as demand elasticity, price-setting decision-making or public policies, for instance.

4.2.2 The Impact of Price Sensitivity of Demand

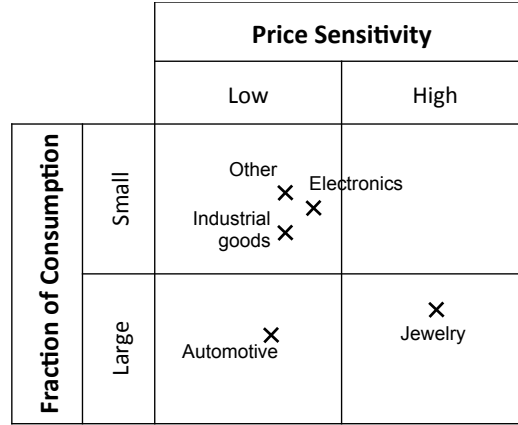
Another aspect of markets that cannot be easily taken into account by static metrics is the notion of feedback, and in particular the idea that demand is also sensitive to supply and price evolutions. The economic concept of elasticity is a useful abstraction to analytically understand the extent to which a price change affects demand. Yet elasticity values are not observable *per se*. Instead, they can be inferred from revealed preference studies, by looking at how the consumption reacted to prices over time for instance.

The **M:5** model has been designed to account for demand elasticity and adjust demand scenarios to supply and price changes, hence incorporating a dynamic feedback in the market behavior. It is particularly interesting to adopt a manufacturer's point of view and evaluate the impact of other sectors' behaviors on the overall market, especially when supply is constrained and leads to price volatility.

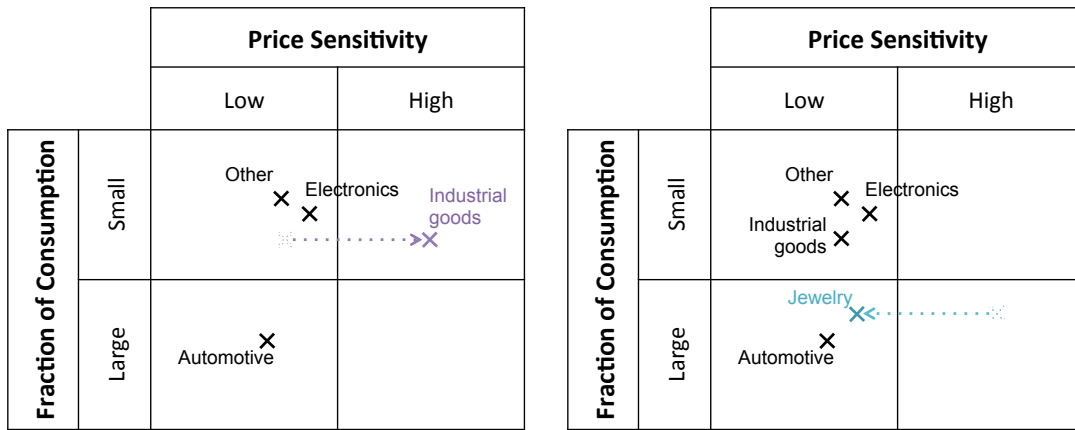
The following analyses have been designed to evaluate the impact of price elasticity of differently-sized demand sectors. Using the case of the platinum market, the demand has been split into five different sectors that have different sizes and price sensitivities. The price sensitivities of two different sectors — one representing 10% of the total demand and the other 30% — have been changed, while the market exposed to the same demand growth rate, in order to compare the mitigating or worsening effect of price sensitivity on price levels and volatility.

The general conditions of the analysis are the following:

- The market is moderately concentrated ($\text{HHI} = 20\%$).
- The demand sectors grow at a 4% annual rate.
- There is no recycling stream



(a) Original demand sectors distribution.



(b) Demand structure with an increased price sensitivity for a small sector.

(c) Demand structure with an lowered price sensitivity for a large sector.

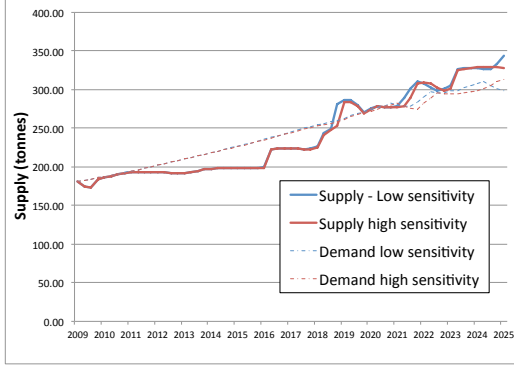
Figure 4-23: Three different *price sensitivity/sector size* distributions of demand sectors to see the impact of price sensitivity on the overall market behavior.

- The jewelry (30% of total demand) and industrial goods (10% of total demand) demand sectors are shifted from a low to high price sensitivity while the others are maintained at a moderate elasticity.

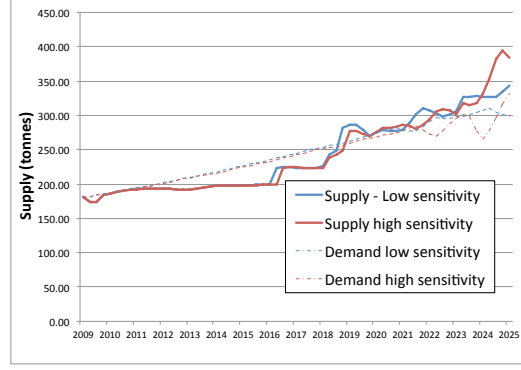
The model outputs, namely supply and price, are presented below:

These simulations provide different insights concerning the effect of price sensitivity on the market. In particular, the following remarks can be made.

When the price elasticity of a relatively small sector (in this case, representing only 10% of the global demand) is changed, the effect on both supply and price are not particularly noticeable. Supply, price and demand curves present similar evolutions in both cases — although a slight delay can be observed in the case where the price elasticity is high. In particular, if prices follow a similar pattern in both cases, as

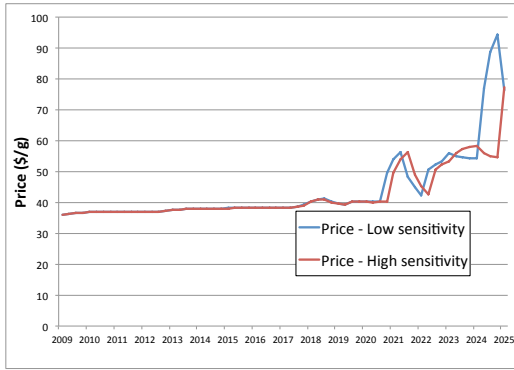


(a) Supply and demand comparing the two cases where a small sector has a low or a high price sensitivity, as shown on Figure 4-23b.

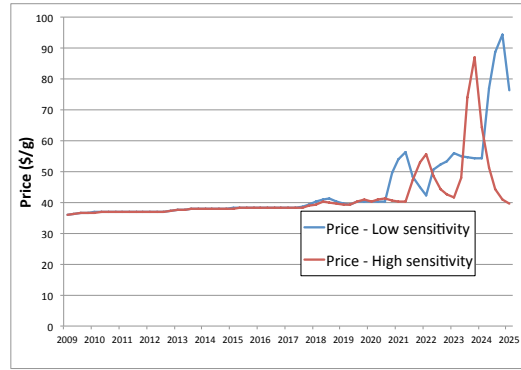


(b) Supply and demand comparing the two cases where a large sector switches from a high to a low price sensitivity, as shown on Figure 4-23c.

Figure 4-24: The supply and demand curves obtained by the model when varying price sensitivities as indicated on Figure 4-23.



(a) Price evolutions in the two cases where a small sector switches from a low to a high price sensitivity, as shown on Figure 4-23b.



(b) Price evolutions in the two cases where a large sector switches from a high to a low price sensitivity, as shown on Figure 4-23c.

Figure 4-25: The price curves obtained by the model when varying price elasticities as indicated on Figure 4-23.

illustrated on Figure 4-25a, the higher elasticity slightly postpones the price peaks.

When the price sensitivity of a large sector — such as jewelry in the case of platinum, representing 30% of the total demand — is changed however, the effect on the market is much greater.

On the one hand, Figure 4-24b clearly illustrates the fact that demand is more elastic to price, since the demand curve in the case of a high price sensitivity presents more variability. As a result, the supply curves also present slightly different patterns.

On the other hand, the price curves on Figure 4-25b are particularly illustrative of the effect of price sensitivity on the overall market. More specifically, if a large sector

has a high sensitivity to price, it will lower its demand when price increases and hence lead to a price decrease. As illustrated on that figure, this leads to a higher price volatility, since the sector is more reactive to price changes and impacts the general price level due to the large size of the sector.

The simulation illustrates the fact that a manufacturer’s welfare also depends on other consumers’ behaviors. Depending on several parameters such as size and growth rate, the impact of higher prices may lead to different market dynamics and ultimately to more or less important price volatilities.

Using the case of the platinum market, the fact that the jewelry sector — representing a large fraction of the annual demand — has a high price sensitivity, as has been historically observed, can have the effect of increasing the price volatility on the market. While there is a positive short-term effect on other manufacturers since prices decrease when demand for jewelry is lowered, the overall behavior of the sector and its reactivity to price changes actually may increase the risks for other manufacturers by making the market less stable.

The case of price sensitivity is also a good illustration of what can be gained from using the **M:5** model, instead of metrics-based approaches only. Incorporating market dynamics and interactions between supply, demand and price refines the insights on markets, and in particular can help decision-makers assess when a market characteristic is indeed a source of concern — in this case a high elasticity demand sector creates high price volatility, but only if the sector is large relatively to the rest of the demand.

4.3 Policy Implications of Materials’ Criticality

This section explores the policy implications of materials criticality, in light of the methods developed and modeling results obtained.

To understand the policy context of the question of criticality, it is important to revisit the original question. The importance of thinking about criticality from a firm’s perspective is that the instability and uncertainty that can arise from critical materials markets can have great economic implications not only for firms, but also for suppliers and external actors — such as governments. Yet, conventional analyses have tended to focus on the implications of such issues for the economy as a whole. This section hence offers a more comprehensive outlook of the policy landscape surrounding the market for critical materials.

The Structure-Conduct-Performance framework applied to critical materials markets in Section 2.1.3, illustrated the concept that markets are influenced not only by their primary actors, but are also shaped by external factors such as that of governmental policy, and hence have wider policy implications. The following sections use components of this framework to comprehensively suggest and evaluate the different types of policies — whether private or public — that can be implemented, as well as their possible limitations.

While supply disruptions and price volatility are primary manifestations of what is usually characterized as *materials criticality*, price volatility information alone does not afford sufficient insight for the task of devising an efficient mitigating policy. Moreover, some of the current rules of thumb for both evaluating and treating materials criticality — such as a focus on market concentration — are potentially too simplistic in both conception and implementation when the market system as a whole is taken into consideration. It then becomes important to establish the circumstances under which such concerns are legitimate in order to avoid unnecessary policy interventions.

The risk-assessment and mitigation process thus has to be decomposed in different phases, namely to understand *(a)* whether or not there is a risk, *(b)* what the magnitude and the consequences of that risk are, and *(c)* what types of action can be taken in order to mitigate the effects of the risk, or lower the risk, if possible. The tools developed in this research have been designed to accomplish those tasks.

A particularly interesting feature of the model is that it aims at understanding what the price actually means in the context of critical materials, as well as how this understanding can help guide the decision-maker towards achieving the policy goal of all market actors: surviving by making the largest profit possible.

Using a decision tool such as the **M:5** model is particularly relevant when recognizing that market circumstances continuously evolve and that individual actions have a broader impact on the market as a whole because of market dynamics and interactions. Policy-making in the context of critical materials markets should be done in an *adaptive* way; the use of a model such as the **M:5** model, incorporating dynamics, is hence valuable in the pursuit of this goal. An individual decision-maker can use the model to *(a)* know what to monitor on the market, and *(b)* compare the different policies that can be effective or not with the different circumstances surrounding the market, and this on a regular basis.

Given the constraints arising from the ways in which risks have to be assessed in the case of critical materials, this section suggests and assesses risk-mitigating strategies

that the different market actors — namely suppliers, consumers and policy-makers — can implement, using model insights and reflections on critical materials’ markets.

4.3.1 Policies to Influence the Supply Market Structure

Historical events, reinforced by model simulations, have shown that several structural characteristics of materials’ markets present inefficiencies that ultimately can lead to higher risks of supply disruptions and price excursions: the number of suppliers on the market, the barriers to entry, and the cost structure of the different actors. This section aims at giving ways in which market actors may influence the structure of such markets to mitigate the risks associated with the structural inefficiencies of materials’ supply.

Addressing the Issue of “Natural” Market Concentration

One of the most important concerns on the supply-side of materials markets is the influence of high market concentration on market efficiency. Mining markets are characterized by very constrained supply structures, arising from *(a)* physical constraints due to the geographic distribution of resources and *(b)* high investment and capital requirements. Supply concentration can lead to more substantial price excursions during periods of rapid growth in demand, as has been seen in the case of palladium presented in Section 2.2 and in the results of model simulation presented in Section 4.2.1 for instance. While concentration cannot systematically be considered as a *structural* market characteristic, especially if the monopolistic or oligopolistic positions of certain suppliers have been acquired through a particular conduct, this section only considers cases where market concentration arises due to the natural distribution of resources.

Policies that can be adopted in the case of a “natural” mono- or oligopoly are limited however, because of the very nature of the problem.

Private actors, particularly suppliers and consumers, may have an incentive to intervene to mitigate the *effects* of a “natural” mono- or oligopolistic situation on the market, rather than try to correct the situation itself. In particular, recycling appears to be an efficient policy, since adding a secondary supply stream to the primary production can have a risk-mitigating effect — particularly in the case of supply disruption — as observed by Alonso (2010) and shown by model simulations. Interestingly, the amount of material that can be recycled at each period depends

on past consumption and not directly on supply nor supply structure — though one could expect price to influence the rate of recycling, providing a more or less attractive incentive to develop a sustainable and efficient recycling stream.

For manufacturers, improving recycling can be a beneficial policy for additional reasons. In particular, increasing the recyclability of material or making the recycling process more efficient has a positive influence on the sustainability aspect of the material, which can be interesting in particular if regulations encourage the use of secondary material.

An important aspect to consider when implementing a recycling policy is the notion of timeframe. Indeed, materials can only be recycled once the products they were embedded in reach their lifetime. Such lifetime may be difficult to forecast and hence it becomes difficult for manufacturers to evaluate precisely how large the secondary supply will be at a given time. Moreover, the efficiency of recovery highly depends on the products the material was used in, as well as on the process required to recycle and re-condition the material so that it can be used again.

Another important question arising when considering the implementation of a recycling stream is that of who should take on the recycling process. While manufacturers have definite advantages to encourage recycling policies in order to stabilize supply and prices, and potentially improve the material's sustainability impact, the cost of recycling may be prohibitive or the facilities to accomplish a sustainable recycling stream too capital-intensive. On the other hand, suppliers may have an incentive to undertake recycling operations as well; if the recovery process is compatible with mining and processing processes, it can be beneficial to increase revenues by providing a secondary supply stream.

Enforcing a more efficient recycling stream could also be undertaken by governments when there is a risk of price excursion or volatility.

Using the model to estimate the adequate recycling rate may prove useful to implement the most efficient strategy, while considering the associated cost to the industry or external recycling companies.

Alternatively, a policy that can be adopted by manufacturers to mitigate the effects of price instability or supply unreliability is that of stockpiling the material needed for their projected demand. By buying material in advance, it ensures a constant price for a given period of time, hereby stabilizing the supply stream and expected value of the material.

The risks associated with such policies is that of large potential financial losses if the material devaluates over time. Moreover, if many manufacturers adopt this policy, the sudden demand increase may lead to an increased instability and higher prices

as a result of the additional pressure on supply. Such negative effect of “safety stock” policies have been observed during the palladium crisis, as mentioned in Section 2.2 and can have a dramatic effect on the economy.

The Issues Associated with Barriers to Entry

Another structural issue of critical materials markets is that of high barriers to entry. The mining industry is highly capital-intensive and, even if a large deposit of the material is found, it can be extremely expensive to open a new mine, not only because of equipment and infrastructure, but also because of the very steep learning curve that makes it harder for new actors to penetrate the market when there are established actors already operating that have acquired efficient mining techniques and knowledge. An example is that of REEs: China has been the major producer of REEs for over 20 years and has acquired a very broad and deep knowledge concerning the mining and processing of those materials, since the government had made the mining of REEs a national priority (Program 863, 1986). Other nations with natural deposits need to promote the procurement of this knowledge by their indigenous firms in order to rapidly become competitive at a cost comparable to the current market price.

Governments of consuming countries can put in place policy strategies to lower those barriers to entry, and hence allow for new actors to enter the market.

On the one hand, direct subsidies can be provided to prospective suppliers in order to lower the financial requirements for the opening of a new mine. The risks associated with such policies however are the financial risk if the prices of the materials fall before the mines are able to reach a sustainable supply level, as well as possible Stiglerian regulatory capture (Stigler 1971) by affected industries and mining groups that could create institutional inefficiencies. However it can be urgent to quickly diversify the sources of supply of some critical materials, and subsidies or favorable tax regimes can help achieve that goal in order to at least get the mines to a good functioning level.

On the other hand, governments may decide to fund research for the development of the mining industry in order to lower the barriers to entry that have to do with knowledge requirements. As mentioned in the previous section, the broad impact of REEs on many different industrial sectors for instance would motivate governments to subsidize that industry (Busch 1999). Little risk is associated with such a strategy that can benefit the overall competitiveness of a nation when the material considered is very strategic.

Such decisions can be informed by the use of a model such as the **M:5**, since it provides guidance to evaluate the extent to which the entrance of a new actor will

mitigate the criticality risks, and what the required cost level might be. The user should however acknowledge the fact that the **M:5** model is currently designed to perform qualitative analyses, and that its quantitative aspect may be refined by further modeling developments, as suggested for instance in Section 3.4.3.

The Impact of Cost Structure

Finally, the cost distribution of the suppliers is another feature of market structure that can have a great impact on market behaviors. This has been illustrated with the model in Section 4.1.1, where we show that price volatility is dramatically influenced by the scale and efficiency of the marginal producers. If those producers are both small and costly, then small demand changes can lead to major price swings. A direct consequence of higher costs is of course higher price levels, which can have a dramatic impact on manufacturers if demand increases.

One avenue for suppliers to mitigate this effect would be policies promoting technology change, particularly technologies improving mining and extraction efficiencies. More efficient mining techniques will lower the costs of extraction and ultimately lead to increased rates of extractions and possibly lower price levels. Suppliers have an incentive to lower their operating costs since it increases their marginal profit as well as helps maintain the prices at a lower level and hence limiting the entry of new actors. Distortions may be introduced when promoting such policies however; in particular, more ‘aggressive’ pricing policies may lead to non-competitive market behaviors, as will be mentioned in Section 4.3.2. The case of REEs is an extreme illustration of such a distortion, yet one would not expect in general that technology changes would systematically lead to monopolistic behaviors.

The shape of the aggregate supply curve has large policy implications for suppliers; indeed, price evolutions are directly influenced by suppliers’ extraction costs, which has an effect on profitability and production decisions. Policy implications for suppliers are related to extraction choices — more specifically, cost levels of operating suppliers have a direct impact on individual mines, and may encourage either a higher or a lower rate of extraction. It can even lead to the closure of a mine, if prices are driven down too far.

More generally, the cost structure of suppliers may have a large impact on the overall behavior of the market. In particular, simulations have shown that various operating cost levels as well as marginal cost curve steepness may lead to significantly different price evolutions, and governments of supplying countries may consider that helping the suppliers to become more cost-efficient can help the overall economy.

Busch (1999) would argue that, in the case of REEs for instance, their importance for many different industrial sectors for instance would justify the establishment of subsidies for that mining industry.

On the one hand, favorable tax regimes and subsidies for *existing* mines can change the shape of the aggregate supply curve and as a result lower the risks of supply disruption and price volatility. Using the **M:5** model can prove useful for governments to establish the levels of subsidies or taxes to put in place in order to have a significant risk-mitigating impact on the market.

On the other hand, one could envision the establishment of transfer payments between consuming and supplying countries to favor a change in the shape of the aggregate market supply curve and hence lower the risks to the economy and consumers. Distortions may arise from such a policy, if the recipient country does not use the payment to its intended end.

4.3.2 Policies to Affect the Supply Market Conduct

Many manifestations of criticality arise due to the conduct of suppliers. This section seeks to present ways in which private as well as public actors may influence the conduct of critical materials markets actors, to mitigate the risks associated with the inefficiencies of materials' supply.

Tackling Market Concentration Resulting from Suppliers Conduct

First, market concentration can result from a particular conduct. In the case of REEs for instance, the monopolistic position of China has been acquired not only because of a particularly large reserve of inexpensively extractable materials, but mostly from the adoption of a very aggressive mining strategy coupled with a certain laxity in accounting for environmental damages. Discovered in 1787, significant production of REEs only became important around 1965, and dramatically increased in 1985 when China started large-scale production. This is mainly attributed to the implementation of the Program 863 in 1986. According to China's Ministry of Science and Technology, that program was created to "gain a foothold in the world arena; to strive to achieve breakthroughs in key technical fields that concern the national economic lifeline and national security; and to achieve 'leap-frog' development in key high-tech fields in which China enjoys relative advantages or should take strategic positions in order to provide high-tech support to fulfill strategic objectives in the implementation of the third step of China's modernization process" (Program 863, 1986). As a result, a lot of

money was directed at the mining and processing of REEs that appeared very strategic at that time. While the world demand was significantly increasing as more and more uses for those materials were discovered, China became better and better at mining them, increasing their output while driving prices down significantly. As a result, other suppliers — including American companies that were market leaders beforehand — were driven out of business (Hurst 2010) because of a lesser efficiency in the extraction and processing of the materials. This led to the monopolistic position that is still unchanged today. Moreover, large environmental costs are associated with the mining of REEs. For instance, the exploitation of Mountain Pass's deposits lead to thorium tailings, whose disposal is expensive. The Chinese government has been fairly lax — at least until recently — in the enforcement of most relevant environmental regulations, hence helping to cement a dependency upon the Chinese supply by undercutting competitors.

Governments first have a possibility of directly sanctioning the monopolistic behavior of the supplier. In the case of REEs, it seems very plausible that the quotas and other policies impairing exports were designed by the government in order to favor the competitiveness of China. If true, this behavior could lead to the presentation of a case at the WTO, with sanctions are a potential result. Using an international organization such as the WTO in order to regulate and control the behavior of a market actor behaving in a way that impedes competition can help mitigate the negative effects on the market. However recent developments have shown that this is not an easy or rapid process and seems to be slowed down by bureaucratic issues. Indeed, Japan, the United States and the European Union jointly brought a dispute case to the WTO in March 2012, regarding China's policy concerning the rare materials' supply (*China's Rare Earth Industry and Export Regime: Economic and Trade Implications for the United States* 2012). The WTO agreed in late July to consider the claim and verify whether or not China is constraining exports in order to favor its domestic production in a non-competitive way, but no actual measures have been taken as of today, however.

Another policy would be that of international coordination. In a monopolistic situation, all the countries rely on one single nation whose mining industry can be very much controlled by its government — in the case of both REEs and palladium, for instance. In order to mitigate the risks, the importing countries need to coordinate their demands and together find arrangements in order to ease the pressure on the supply side; hence Japan establishing a new import contract with Kazakhstan for instance.

If international coordination is key in such situations, it is however insufficient to

fully mitigate the risks because it does not solve the fact that most of the supply cannot come from other places, at least not in the short-term. But common claims and import policies can help add pressure on the monopolistic supplier and accelerate the process of establishing competition. Such policies might however lead to an Olsonian collective action dilemma (Olson 1984) since the issue of a critical material's supply can affect many countries and the chosen common action might not be in the best interest of the actors; diffuse interests and concentrated costs of accomplishing increased coordination and fruitful negotiation among actors may not lead to an socially optimal outcome.

One could also envision the creation of an international stockpile to mitigate the impact of generalized supply disruptions; however, this policy would require an even greater amount of coordination and raises many issues in terms of where the stock should be located, how it should be split between actors, how it should be regulated etc. There are hence many challenges associated with greater international coordination.

Using the **M:5** model to compare several scenarios of disruptions and their impact on the market — due to a high market concentration — can help governments make decisions as to which of the aforementioned strategies to adopt given the market context characteristics.

Private actors, particularly suppliers and consumers, may also have an incentive to intervene to mitigate the impact of a mono- or oligopolistic situation.

A natural strategy to accomplish this goal would be supporting activities that would lead to the development and introduction of new mines that have the potential to operate at a comparable cost and produce a significant amount of material. The impediment to the implementation of such policies is the high cost of opening a mine, though high prices as well as a high demand for the material can provide a good enough incentive to encourage the opening of new mines. Public policies, such as tax credits to favor exploration (i.e., an investment tax credit), accelerated depreciation of operating mines (i.e., a depletion allowance or tax credit) or the development of information collecting activities that would lower the cost of discovery (such as the USGS) could be put in place to reduce the impediments to such policies. As mentioned earlier, distortions may arise due to a possible regulatory capture by private actors for instance. One could expect the overall benefits of diversifying supply sources to be larger than the risks associated with it, however. A tool such as the **M:5** model may prove useful in evaluating whether the benefits of investing in such strategies are large enough to justify such interventions.

Addressing Asymmetric Information

Another aspect of critical materials' markets that arises from actors' conduct is the asymmetry of information. The case of palladium and the Russian stockpile is one example of such asymmetry and the palladium crisis is an illustration of the type of risk that can arise from this market imperfection.

Consumers can be directly impacted by this market imperfection, since the asymmetry of information arises when one or several suppliers have an incentive to limit the information about their production or their stock. There are several policies that can be envisioned to remediate the effect of asymmetric information on consumers.

First, private actors such as consulting firms can be hired and paid to report financial information about the operations of different mines. While mines are usually required to publish annual financial reports, private companies may be able to obtain more thorough data through established partnerships with mining companies, and can hence be hired by manufacturers.

Asymmetric information can often lead to an unreliable supply stream, hence giving manufacturers an incentive to also establish a stockpile in order to mitigate the effect of potential disruptive events in the supply chain. Such strategies had been put in place during the “Palladium crisis” as seen in Section 2.2 and proved particularly risky since the value of the stock exhibited very high volatility. If a price collar or another type of policy protecting against price volatility can be put in place, or if the value is not expected to change too drastically, stockpiling can still be an interesting risk-mitigating strategy for consumers to insure a reliable source of supply.

Alternatively, another policy that could be adopted by consumers is that of substitution, which would imply a change in the technology design. Such a strategy — which will be further discussed in Section 4.3.3 — can be very costly for manufacturers and not always feasible, if the functionality constraints imposed by the product cannot easily be met with a different material (as discussed in Section 2.1.2).

On the other hand, suppliers themselves may have an incentive to mitigate the potential supply unreliability resulting from asymmetric information. Indeed, the resulting risk premium on price may well lead to lower demand for the material. Policy decisions that can be made by suppliers to mitigate such disruptive events — that are for the most part unpredictable — may include business decisions such as the establishment of long-term contracts with manufacturers. This was done by the Russian government in the context of the palladium crisis, in order to ease the market. Indeed, insuring a reliable supply stream for a period of time spanning over several years reduces the uncertainty surrounding the market and hence limits price volatility,

which can be harmful both to suppliers and manufacturers. There are potential risks associated with such a policy, in particular for manufacturers if the contract is binding but technological changes occur, or if prices vary too much — in either direction — from their value of when the contract was established.

Finally, governments may also have an incentive to gain more information about the supply of the material, if the resource is deemed important for the country's economy, as has been presented in Section 2.2 and is summarized below.

First, governments may encourage the opening of a new domestic mine — if the reserves exist — in an importing country, since possessing a domestic source of an expensive commodity can prove very strategic. As mentioned in Section 2.2, the American government adopted that strategy by favoring the expansion the Stillwater mine. The up-front costs required for such a policy are large, yet its cost-effectiveness can be evaluated through the use of the **M:5** model, since the model can provide insights on how valuable a new mine will be on the current market to mitigate the risks encountered. Investing in an existing mine if the costs are deemed too high could be a less-costly alternative that would still enhance the strategic positioning of the importing country. Such an investment might be politically challenging to justify for public actors, but could be undertaken by private companies.

Finally, governments may also encourage the establishment of regular market reports, to enhance the knowledge of the industry. Structures such as the USGS provide regular outlooks on commodities, but usually in a way that is too focused on the short-term and may not be directly usable by firms to make better decisions. Comprehensive reports with longer-term considerations, for instance through the creation of an international third-party structure, may improve the data available to manufacturers to help make better-informed decisions, especially if used in conjunction with a modeling tool such as the **M:5** model.

The Issue of Rent-Seeking and Regulatory Capture

Different policies that can be put in place to mitigate the risks associated with critical materials markets may lead to rent-seeking behaviors that can be particularly harmful for markets (Krueger 1974). For instance, the creation of a stockpile for a strategic material may lead to rent-seeking behavior that would undermine the efficiency of the mitigating policy. This issue has also arisen in the case of REEs for instance, with the establishment of export quotas and the hold put on Japanese exports. Such behavior could potentially be mitigated through the use of transfer payments. Indeed, the main reasons put forward by the Chinese government for the implementation of stricter

quotas is the domestic environmental impact of mining; one could hence envision transfers from importing countries in order to compensate for those externalities and reduce the pressure added on the market. Yet other factors are certainly at stake, including the need to save REEs for domestic production, as well as possible political conflicts that may not be easily solved via transfer payments.

Related to the notion of rent-seeking is that of regulatory capture. According to Stigler (1971), firms may have an incentive to encourage governmental intervention in order to limit the entry of new actors in the market as well as establish tariff regulations. In particular, if the commodity is important for a large portion of the economy of a country, it can lead the government to undertake important regulatory actions, subsequently increasing the risk of regulatory capture by the industry. Similarly, existing mines may have incentive to encourage tightened mining regulations since it may drive up costs and concomitant barriers to entry, hence limiting competition.

4.3.3 Influence of Public Policy on the Consumers Side

Several policies can also be developed to affect the consumers' side of the market, particularly if the material is of strategic importance to different stakeholders or that there are security externalities associated with its extraction and use.

Strategic Importance of the Material

As mentioned in Section 2.1, critical materials can be of significant importance to numerous actors of the economy, both private and public.

The core challenge of materials criticality for manufacturers is, of course, the reliance of the product and the resulting production strategy on reliable availability of a critical material. For instance, a car manufacturer is directly impacted by a supply disruption in the PGMs' markets since there is a heavy use of precious metals in catalytic converters.

Manufacturers need to make decisions about materials on a regular basis, and hence forecast their future need for a given material depending both on the design and production requirements, and on the supply stream reliability. As model simulations — as well as historical trends — show, higher rates of demand lead to greater risks of supply disruptions and resulting price excursions. Comparing different demand scenarios and evaluating their relative impact on the market, in order to assess the best use of materials in product design hence becomes an important policy aspect for critical materials' users.

If a material's market appears to present a high risk of supply disruption or price excursion, a manufacturer can hence adopt different types of policies to mitigate the effects of criticality on itself. One can be the adjustment of the demand for the material, so as to lower the reliance on the material. This can be accomplished through the elaboration of a different product design that does not use as much material. Another possibility, which is often adopted, is that of material substitution. Section 2.1.2 has raised the question of functionality constraints and the trade-off between material's performance and cost that needs to be evaluated by manufacturers, in order to make more comprehensive decisions about materials and product design. In particular, these policies are better informed by the incorporation of supply-related information about materials. The main risk associated with such policies are that of cost, since changes in product design as well as finding feasible alternatives may be challenging for manufacturers.

The strategic importance of critical materials and the impact they have on several industries could also lead governments to develop risk-mitigating strategies addressed directly to consumers.

First, creating a domestic stockpile of the element in order to sustain the country for a long period of time could greatly increase security of supply and insure a continuous production of manufactured goods using the material. There is however a financial risk associated with it since the material might get devalued because of market fluctuations, as mentioned in Section 4.3.1. Yet, if there is a high risk of price volatility — arising from different circumstances and informed by the implementation of different scenarios in the **M:5** model for instance — having such a stockpile for domestic manufacturers would stimulate the industry without impairing the economic health of firms.

It could however increase the risk of a Stiglerian regulatory capture by industries that are in need of a specific material, since those interest groups would benefit from regulations favoring their own industry through subsidized raw products, as compared to others that may not need the same materials (Stigler 1971). One could hence argue that such an insurance policy should only be implemented if the material has an impact on industries that have a strategic role in the domestic economy; this relates to Busch's discussion (Busch 1999) about national champions since it raises the question of whether or not governments should favor certain industries as opposed to others.

A perhaps more radical strategy would be that of material substitution since the model shows that lower demand reduces the risks of disruptions and price volatility. Governments could in particular fund research and development to mitigate the risks coming from the functionality constraints that lead a specific industry to rely heavily on a particular material. For instance, one could envision federally funded research on

permanent magnets to lower the reliance on REEs, since they are the only economically and technically viable option to reach the level of magnetism to sustain wind turbines operations, and yet are inherently highly critical due to their constrained supply.

Security Externalities

Critical materials can also have strategic implications in that they are often times heavily used in industries that supply national security infrastructures and technologies, such as military equipment. The government influence is hence not that of simply mitigating risks, but rather the addition of a new demand sector. It can hence be important to use a model such as the **M:5** model, in order to compare the effect of the addition of a governmental demand sector to the market and evaluate the relative impact of growth rate and elasticity, before making purchasing and deployment decisions.

Additionally, security externalities may arise because of where the material is mined. The nature of the mining industry is such that the distribution of supply sources depends upon geological properties. As a result, countries with limited or inexistent natural deposits are mostly reliant on *imports* to procure the necessary commodities for industry actors — private or public.

Security risks such as labor or political unrest in supplying nations may add frictions on the market and have a negative impact on the supply chain for the material, potentially leading to disruptive events. Such events can be harmful to markets, as was the case with the recent strikes in South Africa as mentioned previously in Section 2.3.2, but also violate domestic or international rights. The Dodd-Frank Act (2010) is an example of policy that governments may adopt to mitigate such externalities. By labeling gold, tantalum, tin and tungsten as *conflict minerals* because extracted in the Democratic Republic of Congo (DRC) where the political unrest is great, the U.S. government insured that its domestic manufacturers would limit contracts with suppliers from the DRC and hence limit the negative impact of the externality on the American economy. Such policies present the risk of affecting domestic production, since it directly constrains the supply stream and may result in increased procurement costs — if for instance new (and more expensive) mines are required to satisfy the demand.

Mitigating the negative effects of security externalities may also require international coordination, especially if the geopolitical situations of the supplying countries are against international regulations such as those of the WTO. Yet international coordination also presents limits, as mentioned in Section 4.3.2.

Chapter 5

Conclusions and Future Work

In a economy that increasingly relies on materials for productivity and new energy sources, it is essential to be able to make informed purchasing and design decisions when it comes to material use. While some materials markets are well-established and regulated, and hence can sustain the demand with a reliable stream of supply, others exhibit constrained behaviors that can emerge from many different sources. Materials become *critical* when the supply unreliability or price volatility become too risky for a manufacturer, given his own demand.

The review done of current approaches to criticality shows that existing approaches are inadequate to the challenges faced by firms making decisions about materials.

On the one hand, static — or metrics-based — approaches are useful in that they quickly and easily provide an overview on the market. However, their static nature limits their ability to reflect the interactions between supply, demand and price, and, thus, runs the risk of overlooking their potentially mitigating or risk-enhancing effects on the market.

As illustrated in Section 4.2, metrics can be misleading when indicating a source of concern — such as market concentration — since the impact of such market structures upon the market is dependent on the entire context.

As a result, while metrics provide a good way of quickly screening for potential risks on a material’s market, they are not sufficient to grasp the full picture and, thus, make a well-informed decision about a material.

Although static approaches are limited, it is also the case that the current dynamic approaches to criticality do not necessarily provide the flexibility and insights required for *manufacturers* to make decisions about materials.

First, while economic abstractions are useful to reflect on markets in general and long-term market trends, they do not provide a short- to medium-term approach to

criticality that would help manufacturers make a decision about a material in a timely fashion. Moreover, most of the economics literature exploring the issues of criticality has used as its unit of analysis the economy as a whole. Thus, conclusions of such analyses speak to the actions necessary to sustain and maintain that economy. What has been missing, however, is an approach that takes the firm as the unit of analysis, which is a challenging thing to do because of the amount of specificity (treated by financial models) and detail (addressed by system dynamics models) required to obtain meaningful insights.

Financial-based models are restrictive in the sense that they focus on very short-term reflections on market and rely on regression-based forecasts to infer either demand or supply, and hence are lacking the notion of feedback and a longer-term perspective that is necessary for firm operational planning.

System dynamics models offer the most comprehensive overview of materials' markets and incorporate a large number of actors, behaviors and trends. As a result however, the time and resources required to build such models for one individual material make it difficult for manufacturers to gather enough information about all necessary materials and make informed decision in a timely fashion.

This gap in the existing literature and work on materials criticality led to the current research effort, which was focused on the development of a tool that could be easily used by manufacturers to make quick, yet sufficiently well-informed, decisions on different materials.

One of the questions motivating this work can be summarized as follows:

To what extent is it feasible and beneficial to adopt the tools of microeconomic theory to get new insights into the dynamics of materials availability?

An adaptive tool was developed to model materials markets and provide insights about mining economics to manufacturers. The model, fully explained in the text and appendices, has been grounded upon economic theory, and is framed as a supply-demand model. It also draws on observations of mining markets to incorporate common imperfections, and implements a market pricing strategy that was deemed most suitable.

While the **M:5** model has limitations, results and analyses show that it is a useful tool to advance understanding of market dynamics and behaviors, while making limited data requirements of the analyst. Such an approach thus appears both feasible and beneficial, since — as shown in Section 4.2 — it can inform decision-makers better than static metrics, and has the advantage of being both tuned for manufacturers and requiring only a limited amount of data.

A second question motivating this work was:

In the context of critical materials, how can a better understanding of market dynamics inform criticality assessments and risk-mitigating strategies?

To answer this question, many scenarios were developed and simulated using the model. Chapter 4 (a) presents some of the obtained results, (b) identifies potential sources of concern — and associated contextual parameters — for manufacturers, and (c) offers risk-mitigation strategies.

Two key findings of these analyses revealed that subtle interactions among materials markets structure lead to important contingencies that must be explored when considering criticality risks. First, while market concentration is widely viewed as increasing the risk of unexpected price excursions in critical materials markets, these effects are only significant under circumstances when consumption is expanding rapidly (i.e., high demand growth rates). Second, the structure and composition of demand must be taken into consideration when exploring criticality risk. Differential price elasticities of demand, in conjunction with the overall market shares of consuming sectors, have a strong influence on the apparent volatility of a materials market.

Moreover, some mitigation strategies have been identified in this work.

First, recycling has the effect of reducing price excursions and mitigating severe supply disruptions. The efficiency of recycling has a large impact on the mitigating effects of this potential strategy.

Second, the model analyses confirm that new mine openings can be beneficial to reduce the market concentration and hereby mitigate disruptive events on the market. Yet this benefit is only apparent under the contingencies as mentioned previously, for instance under circumstances where consumption is increasing rapidly.

Finally, policies that change the cost curves of mines, for instance regulation or subsidies, have a great impact on the market behavior. Scenarios should hence be developed and implemented in the model to compare the relative effect of these policies on the market and evaluate their benefits versus their costs.

This work has produced and tested a tool designed so that manufacturers and policy-makers can make better-informed market decisions about materials. By modeling market dynamics and allowing for the implementation of different demand scenarios, this tool enables a decision-maker to compare the relative impact of various policies on a materials market. Since the model does not require a large amount of inputs, it is flexible enough to be used for many different materials, and in a timely manner.

Assumptions about markets behavior and model simplifications — for resource constraints — have been made, and limit to some extent the model’s applicability to

every situation. During the development of the model, we identified a trade-off to assess between an increased model complexity — and concomitant increased accuracy — and the resources needed to (1) implement it and (2) apply it to different materials. Since the motivation of the work was to provide a *flexible* tool that incorporates market dynamics but can easily be used by firms on a short-term basis for planning requirements, this trade-off has led some simplifying assumptions. The following section hence makes suggestions for possible improvements and extensions of the tool, based on the observations of its limitations, pointed out in Section 3.4.2.

Future Work

Design choices made during the development of the **M:5** model present limitations that could be reduced in future model developments. In particular, these modeling implementation decisions limit the utility of the model when seeking to construct reliable *quantitative* forecasts. As has been described in this document, the focus of the model development was, instead, upon constructing a tool whose theoretical foundation would facilitate the development of useful scenario analyses and the insightful evaluation and comparison of *qualitative* market features for decision-makers. However, should an analyst have on hand greater supply and demand information than the **M:5** model requires, there are several opportunities for model refinement what would help to improve the model’s suitability for the exploration of more quantitative results.

One of the main assumptions of the model is related to the handling of stock. The current model treats the stock as a simple bookkeeping instrument, with a very simple strategy, when material stocks are in fact held by a variety of actors pursuant to a variety of strategies, almost all of which are driven by short term price changes. Instead, in the **M:5** model, stock is aggregated at each period and is virtually “sold” — as an additional supplier — at the next period. One improvement could hence be to make the decision of selling the stock price sensitive, and hence incorporate the notion of opportunity costs and investment. Speculation and investment are indeed important aspects of critical materials markets, since they may exacerbate price excursions by increasing demand when prices are higher and increasing supply when prices fall down — for profit-making reasons. Incorporating such behavior in the model could increase the sophistication of the price level calculation; making the selling of stock price-sensitive could be an insightful first improvement to that end.

Similarly to stock, recycling is handled simplistically. Indeed, the **M:5** model does not yet consider that recycling is actually a function of all the material on hand, in that any material not recycled but still on hand could be recycled in the future. Instead, the current model assumes that only some fraction of material found in products produced exactly one (average) product lifetime ago in the past is systematically recycled at a given rate. While an average recycling rate and an average product lifetime for each sector are a legitimate assumption given the complexity of the recycling stream and the underlying decision-making process, one could envision as a first step the introduction of a price sensitivity for recycling. The recycling industry appears indeed to be highly dependent on materials' prices and on the efficiency of the recycling process, and it could be insightful to capture this notion of opportunity cost when handling recycling.

The current model introduces new mines in a deterministic fashion, set in size and capacity and introduced according to a price trigger. A more sophisticated treatment could model a stochastic implementation of exploration and discovery. In particular, higher prices tend to lead to higher exploration efforts and hence to the opening of additional supply sources. While the list of potential new mines is currently an exogenous input of the model, it could be made endogenous and non-deterministic. This would further enhance the coherence of the discovery side of the model, by making use of observational data (developed by the USGS for instance) that suitably parametrizes the theoretical framing of it.

Finally, the price-setting mechanism that has been put in place follows a given rationale, but one could think about exploring other market maker strategies that reflect different market microstructures, such as pure trades, contracts-based markets, cartels, etc. For each material, there are specific various real institutions whose behavior is monitored and regulated, and whose structures are likely not strictly identical. Hence, one could envision the implementation of some flexibility in the way for the market-maker chooses price at each period. While this can be done by directly modifying the formula, it could also be made a model parameter and enable policy-makers to make the price-setting mechanism more finely tuned to the specific market considered.

The high flexibility of the tool, combined with the ease of use due to the spreadsheet format, make it simple for users to tune it and adapt it to their needs. The underlying theory provides a theoretical foundation that already provides good insight on materials' markets, and can be built upon to obtain more refined results if desired.

Appendix A

Constructing and Modeling Mining Supply Curves

In this appendix, we will explain how we approached the construction of an aggregate supply curve for the mining industry, given the different limitations of traditional methods we exposed in Section 3.1.

Discussion of the Conventional Economist Approach

The conventional profit maximization strategy for an individual firm is to produce at the point where the marginal cost of production is equal to the price, assuming that the firm is a price-taker and that the price is above the minimum average cost — otherwise the firm would not enter the market (Nevile 1992–1993). Indeed, profit can be defined in its most simple form as

$$\Pi = p \cdot Q - TC(Q)$$

where Q is the production quantity, and $TC(Q)$ the total cost of production. The first derivative of this expression is equal to zero at the profit maximum, and hence we have

$$MC(Q) = \frac{\partial TC}{\partial Q} = p$$

with MC the marginal cost at the optimal production quantity.

Moreover, the marginal cost curve of a firm intersects its average cost curve at its minimum:

$$AC(Q) \equiv \frac{TC(Q)}{Q}$$

Hence,

$$\frac{\partial AC}{\partial Q} = \frac{\frac{\partial TC}{\partial Q} \cdot Q - TC(Q)}{Q^2} = 0$$

iff

$$\frac{\partial TC}{\partial Q} = MC(Q^*) = \frac{TC(Q^*)}{Q^*} = AC(Q^*)$$

with Q^* the minimum of the average cost curve.

Since it is traditionally agreed that the average cost curve of an individual firm is U-shaped, especially in the case of a mining industry, we can summarize these results with the graph on figure A-1:

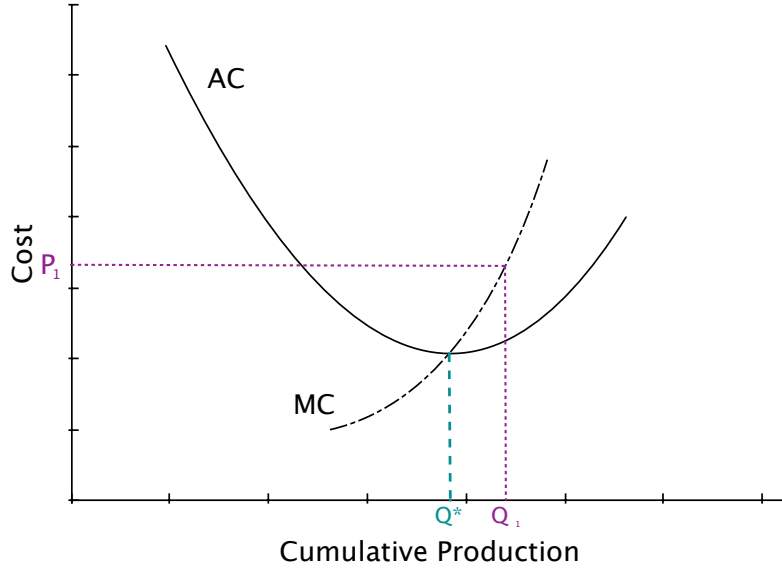


Figure A-1: Schematic representation of individual average and marginal cost curves, with Q^* the quantity at the minimum average cost and (Q_1, P_1) an example of production level where profit is maximized.

Those considerations, however, are only applicable in the short run — long-run supply curves have a different shape, but for this work we do not need to consider long-run supply curves. Indeed, long-run supply curves are by definition not price-sensitive but instead are dependent on economy-wide contextual parameters, such as employment levels. The scope of the model however, is focused on short- to medium-term price-sensitive decisions by individual actors.

Finally, if we consider a market where firms are heterogeneous, we can as a first approximation aggregate the supply curve as figure A-2 suggests (Tilton 1992).

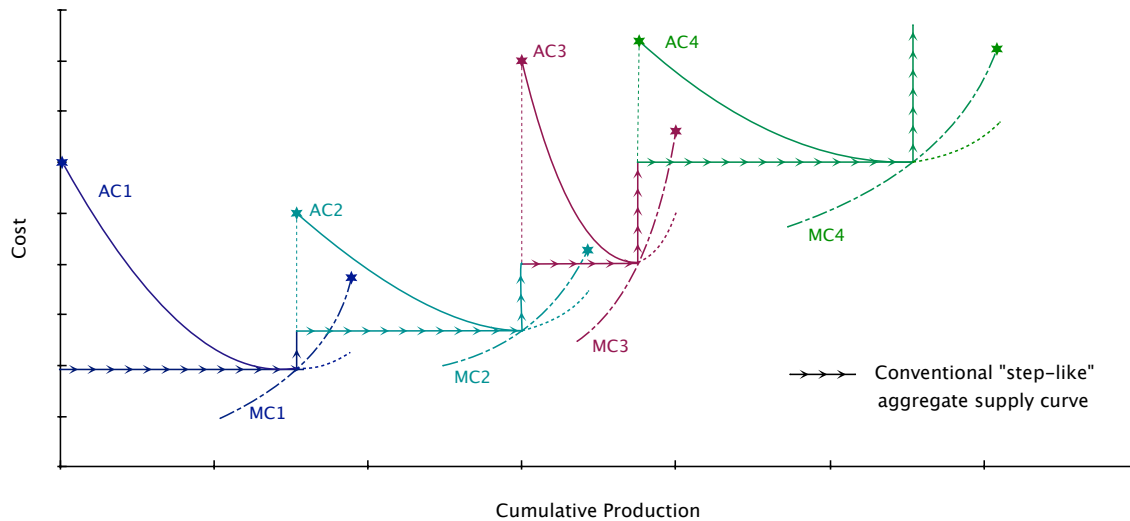


Figure A-2: Aggregation of inhomogeneous supply curves following a stair-step approach.

On this graph, we have represented the aggregation of four different supply curves that we have horizontally summed, since we are considering private goods, while ordering them by increasing minimum average cost. As illustrated on figure A-1, each marginal cost curve intersects the average cost curve at its minimum. The way the supply curve is usually derived is by simplifying the individual curves and modeling them by “steps” (as shown on the graph A-1 by the arrow line). The width of the step is determined by the total quantity that a supplier can produce up to its minimum average cost. Conventionally, past that point, the supply curve — when aggregated — becomes vertical until market prices rise high enough that the next supplier can feasibly enter the market.

We argue, however, that this approach is limited in the sense that it does not allow for a supplier to follow its marginal cost curve, which as we mentioned earlier maximizes its profit, and to increase its production up to its overall capacity (symbolized on graph A-1 by a star). The flat part of the step, in the conventional representation, seems to impose a production and operating cost “ceiling” that is inconsistent with the kind of flexibility that most firms have to increase working hours at times of high demand. We will hence discuss how to get around this limitation in the next paragraph.

An Approach to Overcome the “Verticality Issue”

As we pointed out earlier, ending an individual supply curve by a vertical line, modeling the impossibility of producing above the minimum average cost, does not allow for a larger production that would be desirable despite the higher cost it represents. Indeed, in order to maximize profit, suppliers tend to follow their marginal cost curve once they have produced at least the quantity for which the average cost is minimal. Hence, our modeling approach has been first, to allow suppliers to follow this marginal cost curve until the next supplier enters the market — at least when assuming complete information on the market — and, second, to shift the supply curve accordingly, since there is additional production. The resulting curve is shown on figure A-3.

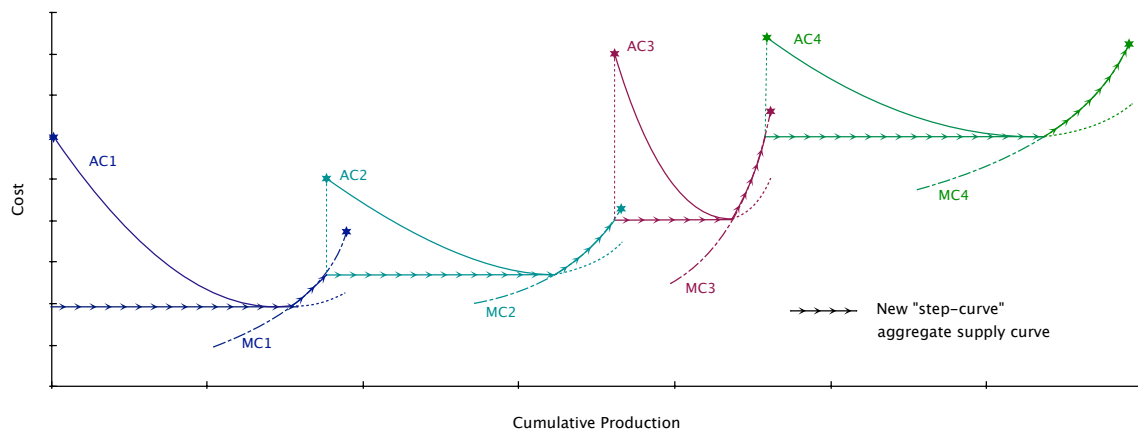


Figure A-3: Aggregation of inhomogeneous supply curves following a stair-curve approach.

This time, past the minimum average cost, a supplier is able to “over-produce” by following its marginal cost curve, which increases the total production of each individual supplier. As a result, different levels of demand will lead to a lower price than the one that would have been obtained following the curve on figure A-2, since the curve has shifted to the right.

Now it would be interesting to understand why we can consider that an individual supply curve prior to the minimum average cost can be considered as flat, when looking at it non-instantaneously.

Reflections on the Flat Part of the Supply Curve

Realistically, firms cannot produce at a constant cost and have to follow their average cost curve until its minimum. Hence, it seems that following a “step-curve” supply curve is not accurate either. Instead, the real supply curve should be as shown below on figure A-4.

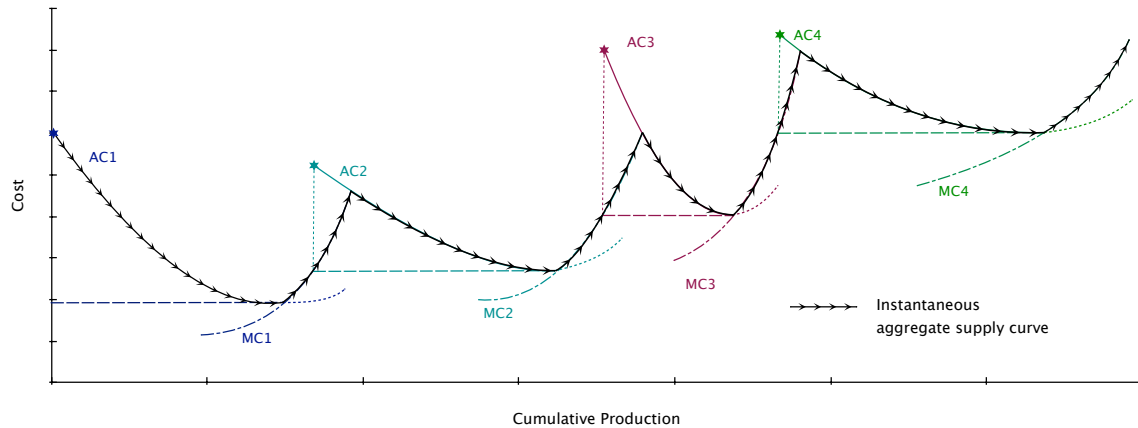


Figure A-4: Aggregation of inhomogeneous supply curves following the average and marginal cost curves.

While on an instantaneous scale individual firms do have to produce following the highlighted curves, such curves are actually unstable. Indeed, if we take the case of the first supplier, he will have an incentive to keep producing following its marginal curve until either the capacity is attained or the cost is equal to the average cost of the supplier 2. But if that is the case, since supplier 2 has an incentive to enter the market, he will at least increase his production so as to operate at the minimum average cost. Because of this, the first supplier will have no incentive to produce above the second supplier’s minimum cost, and will hence stop at the “step” previously described.

As a result, we have two cases at hand, depending on the demand level:

- If the demand intersects the marginal cost curve of the first supplier before the latter meets the next average cost curve, then the second supplier does not enter the market.
- If, however, the demand is above that intersection point, then supplier will have an incentive to stop operating at the step, and supplier 2 will operate at its optimal point — i.e. its minimum average cost.

Hence, when looking at supply curves at a non-instantaneous timescale, we can model the supply curve with a “step-curve” approach since it is its stable state. The

curve depicted on figure A-3 is thus relevant in the short run, for non-instantaneous decisions, which is appropriate in our study.

Appendix B

Derivation of the Supply Curves and Interpolation of Marginal Cost

This appendix explains how the individual cost curves were constructed and, more specifically, how the inverse function of the marginal cost curve — used to calculate the production at each period as presented in Appendix C — was implemented.

Modeling Design Objectives

The general design objectives of the model in terms of supply curve algorithms have been as follows:

- The implementation of a relatively simple analytical functional form for the supply curves that can still cover a wide range of behaviors in terms of supply quantity and cost, while remaining easy to parametrize;
- Ensuring that the simulated average cost curves are *U-shaped* and have continuous first and second derivatives; and
- To use a functional form so that the marginal cost curve can be easily inverted, so that the level of production that a mine could achieve for a given price is readily computable.

Derivation of the Average Cost Curve

Following standard microeconomic assumptions, the average cost curve of each mine was assumed to be ‘U-shaped’, with a clearly defined minimum. Mathematical formulations satisfying this condition were employed to develop a general formula that could be parametrized to reflect a wide range of operating conditions.

Condition on the Second Derivative

The very first analytic condition the general cost curve must meet derives from the condition that the second derivative of the average cost curve should be positive when average cost is at a minimum, so that the marginal cost curve is upward-sloping when it intersects the average cost curve. Starting with the definition of marginal cost:

$$MC(Q) = \frac{\partial TC}{\partial Q} \quad (\text{B.1})$$

$$\text{yet} \quad TC(Q) \equiv AC(Q) \cdot Q \text{ by definition}$$

$$\text{hence} \quad MC(Q) = Q \cdot \frac{\partial AC}{\partial Q} + AC(Q) \quad (\text{B.2})$$

From the assumption stated above, the first derivative of the marginal cost should be positive at Q^* , the minimum average cost:

$$\begin{aligned} & \left. \frac{\partial MC(Q)}{\partial Q} \right|_{Q^*} > 0 \\ \text{ie} \quad & \left. \frac{\partial^2 AC}{\partial Q^2} \right|_{Q^*} + 2 \cdot \left. \frac{\partial AC}{\partial Q} \right|_{Q^*} > 0 \end{aligned} \quad (\text{B.3})$$

By definition, $\left. \frac{\partial AC}{\partial Q} \right|_{Q^*} = 0$. The condition is hence

$$\left. \frac{\partial^2 AC}{\partial Q^2} \right|_{Q^*} > 0 \quad (\text{B.4})$$

While the condition given in Equation B.4 is only necessary at Q^* , it can be generalized to hold for the function generally, since it carries the desirable condition that the average cost function is convex.

Functional Form of the Average Cost Curve

The condition given in Equation B.4 on the second derivative, as explained in the previous section, is the only condition required for initial modeling purposes. While many functional forms can satisfy this condition, a pseudo-polynomial function fulfilling the condition has been adopted, for it can be tuned depending on the mines and can cover a wide range of production quantities and costs:

$$\frac{\partial^2 AC}{\partial Q^2} = a \cdot Q^n \quad (\text{B.5})$$

where $a > 0$ and $n \geq 0$

Integrating Equation B.4 and using the following condition and formalism

$$\left. \frac{\partial AC}{\partial Q} \right|_{Q^*} = 0$$

and

$$AC(Q^*) = A^*$$

lead to

$$\frac{\partial AC}{\partial Q} = \frac{a}{n+1} \cdot [Q^{n+1} - (Q^*)^{n+1}] \quad (\text{B.6})$$

and

$$AC(Q) = \frac{a}{n+1} \cdot \left[\frac{Q^{n+2}}{n+2} - (Q^*)^{n+1} \cdot Q \right] + A^* + \frac{a}{n+2} \cdot (Q^*)^{n+2} \quad (\text{B.7})$$

Total cost and marginal cost hence become

$$TC(Q) = \frac{a}{n+1} \cdot \left[\frac{Q^{n+3}}{n+2} - (Q^*)^{n+1} \cdot Q^2 \right] + \left[A^* + \frac{a}{n+2} \cdot (Q^*)^{n+2} \right] \cdot Q \quad (\text{B.8})$$

$$MC(Q) = \frac{a}{n+1} \cdot \left[\frac{n+3}{n+2} \cdot Q^{n+2} - 2 \cdot (Q^*)^{n+1} \cdot Q \right] + A^* + \frac{a}{n+2} \cdot (Q^*)^{n+2} \quad (\text{B.9})$$

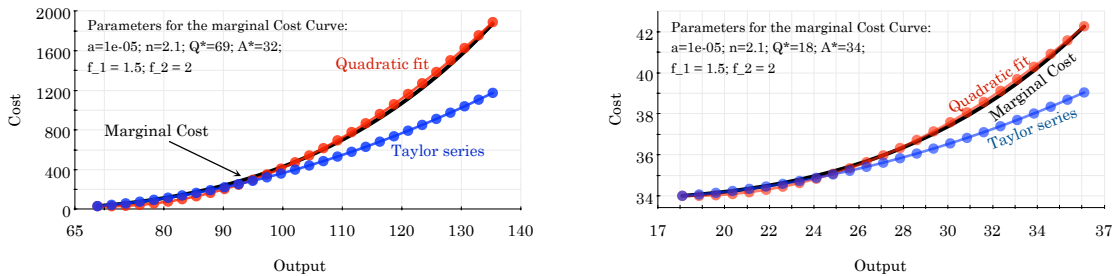
Equations B.8 and B.9 yield an analytic form that can be used to compute total and marginal cost for a mine, given appropriate parameters, over the entire range of possible mine outputs. For modeling purposes, an explicit way of calculating the inverse function of the marginal cost is required in order to be able to compute the output of each mine at a given market price, which must be greater than or equal to

each producing mine's $AC(Q^*)$. Equations B.8 and B.9 are not generally invertible for all n , so an approximation technique had to be devised. The next section will explain how the inverse marginal cost function was modeled.

Inversion of the Marginal Cost Curve

In order to calculate the amount of product a supplier is willing to deliver at a given price (assuming profit maximizing behavior), the suppliers' marginal cost function has to be inverted — the model can hence derive the production quantity of a given supplier at a given price in order to calculate the total supply of the period, as mentioned in Appendix A

The expression (B.9) is not easily invertible, hence the need to approach the inverse marginal cost function. Moreover, a second order Taylor series approximation does not fit the selected function well, as illustrated in Figure B-1. Since the upper limit on production was a modeling parameter, a quadratic interpolation between the output at which average cost was minimized and this upper limit on production (using one intermediate point) afforded a more suitable function. The graphs shown on Figure B-1 illustrate the fact that, given the functional form chose for the marginal cost curve, a quadratic interpolation of the curve provides a better fit than a Taylor-series approach.



(a) Approximation of the marginal cost curve with a quadratic fit and a Taylor series, for $Q^* = 69$ and $A^* = 32$.

(b) Approximation of the marginal cost curve with a quadratic fit and a Taylor series, for $Q^* = 18$ and $A^* = 34$.

Figure B-1: Illustration of the differences between a second-order Taylor series development and a quadratic interpolation of the marginal cost curve. For both sets of parameters shown in these figures, the interpolation approach leads to a better approximation of the marginal cost curve.

The marginal cost curve was hence approximated as a polynomial expression of the second order:

$$\widetilde{MC}(Q) = a \cdot Q^2 + b \cdot Q + c \quad (\text{B.10})$$

$$\text{such that } \widetilde{MC}(Q^*) = A^* \quad (\text{B.11})$$

$$\widetilde{MC}(f_1 \cdot Q^*) = MC(f_1 \cdot Q^*) = M_1 \quad (\text{B.12})$$

$$\widetilde{MC}(f_2 \cdot Q^*) = MC(f_2 \cdot Q^*) = M_2 \quad (\text{B.13})$$

$$\text{with } 1 < f_1 < f_2$$

This approach uses “generic” interpolation points (given by f_1 and f_2) since f_2 is also the factor defining the upper limit of production at each period as a multiple of Q^* . While producers are able to extract more material — at a higher cost than the lowest average cost point — there is still a physical capacity constraint in the short-term production (Tilton 1992).

In general, we rarely observe a mine operating at twice its rated production capacity, but it can vary from mine to mine — a bigger mine may for instance be able to take on a larger portion of “over”-production compared to a smaller mine that hence would have a smaller f_2 . Those parameters have been made flexible, and can even vary over time as the mine slowly depletes.

The three parameters a , b and c of the expression (B.10) can hence be derived, since there are three equations — namely (B.11), (B.12) and (B.13) — and three unknown parameters:

$$a = \frac{1}{Q^{*2}} \cdot \frac{1}{f_2 - f_1} \cdot \left(\frac{M_2 - A^*}{f_2 - 1} - \frac{M_1 - A^*}{f_1 - 1} \right) \quad (\text{B.14})$$

b and c can be inferred from this expression:

$$b = \frac{1}{Q^*} \cdot \frac{M_2 - A^* - (f_2^2 - 1) \cdot (Q^*)^2 \cdot a}{f_2 - 1} \quad (\text{B.15})$$

$$c = A^* - (Q^*)^2 \cdot a - Q^* \cdot b \quad (\text{B.16})$$

Once those parameters implemented, the quantity produced at a specific marginal cost of production can be easily inferred by using the Quadratic Formula, given the expression (B.10) and the fact that we only want a positive production quantity:

$$Q = \frac{-b + \sqrt{b^2 - 4 \cdot a \cdot c}}{2 \cdot a} \quad (\text{B.17})$$

Appendix C

Simulation Strategies

The simulation strategy employed in the dynamic market model is built upon the notion that the market is driven by suppliers independently making production decisions based on apparent price.

Calculation of production for operating mines

1. Start with a given price from the preceding time period, P_{t-1}
2. If $P_{t-1} \geq A_i^*$ for the i -th supplier, compute the quantity the i -th supplier will produce, $MC_i^{-1}(P_{t-1})$, as illustrated on Figure C-1. Note that, because of computational complexity, this inverse function is typically an approximation (refer to Appendix C).
3. Sum over all suppliers to get the supply in the current period, i.e., for all i such that $P_{t-1} \geq A_i^*$; $\sum_i MC_i^{-1}(P_{t-1}) = S_t$.

Price-setting mechanism adopted by a market-maker

A market maker with perfect knowledge of the supply curve could take this approach:

1. Given demand at time t , D_t
2. Find the cost at which ideal supply equals demand:
 - (a) Order the suppliers in ascending order of A^*

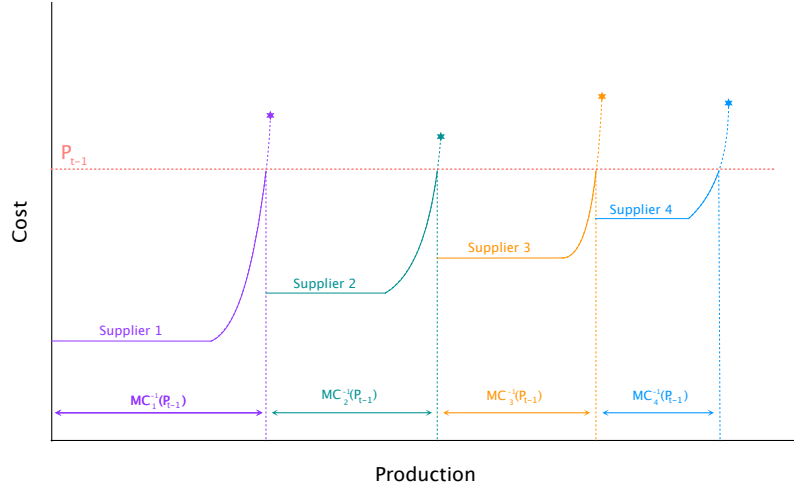


Figure C-1: Illustration of the calculation of production for period t . The total supply at t is given by the sum of each $MC_i^{-1}(P_{t-1})$.

- (b) Compute the “ideal” supply curve where every producer i will produce $MC^{-1}(A_{i+1}^*)$ (*i.e.* up until the next step).
- (c) Compare the quantity ideally supplied with the quantity demanded, by minimizing the difference between the ideal cumulative supply and the demand. The supplier that minimizes this difference is called the “cut-off” supplier.
 - i. If the ideal supply of the cut-off supplier is less than the demand, then the price is calculated as the A^* of the cut-off supplier plus a fixed fraction of the difference between the minimum average cost of the potential next supplier and the cut-off supplier, in order to encourage a larger supply in the next period.
 - ii. If the ideal supply at the cut-off is above demand, then:
 - If the intersection between supply and demand occurs on the step of the cost curve of the cut-off supplier, then price is given by A^* of the cut-off supplier, to which we subtract a fixed portion of the difference between that cost and the minimum average cost of the supplier before him, in order to aim for a lower supply at the next period.
 - If the intersection between supply and demand occurs on the marginal cost curve of the cut-off supplier, then price can be calculated as equal to the marginal cost of the demanded quantity, following that curve.

3. Let each producer whose $A_* \geq P_{t-1}$ and affect to each a stock equal to the difference between what they actually produced (as computed previously, only given the preceding price), and what they should have ideally produced (*i.e.* stopping when their marginal cost equals the minimum average cost of the next supplier).

This price-setting mechanism is illustrated on Figure 3-4 in Section 3.2.2.

Consideration of the mines operating *above* the price

As mentioned in Section 3.2, the actual calculation of supply also includes producers whose A^* is above the price but have been producing in the past and cannot close directly, for more realism. This theory is explained below:

- If the mine is open, price is above marginal cost but the mine produced at a loss in the last period, then the supply is increasing from its last level to the optimal level with a factor tau¹ :

$$Q_t = Q_{t-1} - \frac{Q_{t-1} - Q^*}{\tau}$$

- If the mine is open but price is below marginal cost, the mine will produce at a loss and decrease its production with the same factor tau:

$$Q_t = Q_{t-1} - \frac{Q_{t-1}}{\tau}$$

In parallel, the model calculates a cumulative “loss” (sum of losses and benefits) over a 4-year window when a mine is operating above the price, and if this cumulative

¹The factor tau is calculated specifically for each mine and re-adjusted at each period. It is a downward-sloping linear function of the difference between the minimum average cost A^* and the current price. The equation is hence:

$$\tau = \begin{cases} \tau_{min} & \text{if } p_{t-1} \leq x \cdot A_{t-1}^* \\ \tau_{max} & \text{if } p_{t-1} \geq A_{t-1}^* \\ \tau_{min} + \left(\frac{p_{t-1}}{A_{t-1}^*} - x \right) \cdot \frac{\tau_{max} - \tau_{min}}{1-x} & \text{otherwise} \end{cases}$$

with $\tau_{min} = 1$ for each mine (the value for which a mine will immediately shut down), τ_{max} specific to each mine, and x the lowest fraction of A^* the price can attain before a shut-down of the mine.

loss exceeds a certain factor (specific to each mine) times the “optimal” revenue $Q^* \cdot A^*$, then the mine shuts down.

Finally, a process runs to monitor closings and openings of mines. In particular, mines that have not yet opened will only operate after a certain number of periods (monitored by the user on the inputs page) where the price is above its projected minimum average cost.

Appendix D

Description of the Demand Scenarios

This appendix explains how the model exogenously defines demand, how the user can modify scenarios, and how a notion of feedback based on price elasticity is implemented. First the general form used in the model will be described; the notion of price elasticity is subsequently addressed.

General Form to Describe Demand Scenarios

The model implements demand scenarios through the individual description of different demand sectors. For each sector i , the model user can specify:

- The demand sector growth rate r (in %/year)
- The initial share of global demand $\alpha^{(i)}$ (in percentage)
- A seasonal factor s that specific to each quarter (in %/year)
- Recovery information:
 - Recovery rate (in percentage)
 - Standard lifetime of a product in this demand sector (in years)

The model computes quarterly demand using the inputs of each sector. Each quarter's demand (D_t) is based on the demand in the preceding quarter ($D_{t-0.25}$), multiplied by the growth rate (r) and the seasonal adjustment (s_t). For sector i , the recursion equation is:

$$D_t^{(i)} = D_{t-0.25}^{(i)} \cdot \left(1 + r^{(i)} + s_t^{(i)}\right)^{0.25} \quad (\text{D.1})$$

The initial demand by sector is defined as $D_0^{(i)} \equiv \alpha^{(i)} \cdot D_0$, where D_0 is the total demand for the material at t_0 .

Modeling Price Elasticity

A standard economic metric of the price responsiveness of demand is the price elasticity of demand, defined as the percentage change in demand (Q) for a one percent change in price, or, more explicitly:

$$\epsilon = \frac{\frac{\partial Q}{Q}}{\frac{\partial P}{P}} = \frac{\partial Q}{\partial P} \cdot \frac{P}{Q} \quad (\text{D.2})$$

The model employs price elasticity to create a degree of price responsiveness in what is otherwise a purely exogenous demand function. The functional form of the responsiveness is quite basic, dependent upon how price compares to its historic level. The model calculates a moving, weighted average of price over a number of periods T — defined by the user — and adjusts demand depending on how the simulated price compares to historic levels. The sector’s elasticity sets the impact of price changes on demand and, as is the case for “conventional” goods, increased prices lead to a lower demand and vice-versa. The weights w_i are defined by the user and influence the weighted average of the price to which the simulated price is compared.

When price is higher than its moving average, the model simulates the sensitivity of demand to price with an exponential form, multiplying the period demand (Eq. D.1) by the ratio of simulated price to the trailing weighted average of price raised to the power of the elasticity:

$$D_t^{(i)} = D_{t-0.25}^{(i)} \cdot \left(1 + r^{(i)} + s_t^{(i)}\right)^{0.25} \cdot \left(\frac{P_t}{\sum_{j=t-T}^{t-1} w_j \cdot P_j}\right)^\epsilon \quad (\text{D.3})$$

Since the elasticity is generally negative, we do obtain that higher prices lead to a lower demand for that good.

On the other hand, when prices fall, demand will tend to increase; however using an exponential functional form to increase demand was deemed too radical. Instead, the model implements a linearization of the elasticity expression (D.2) to adjust demand when the price is *below* its moving average, while insuring continuity when the price ratio converges to 1. The moving average for demand is also weighted — the weights are denoted x_i .

$$\epsilon = \frac{\tilde{D}_t^{(i)} - \sum_{j=t-T}^{t-1} x_j \cdot D_j^{(i)}}{\sum_{j=t-T}^{t-1} x_j \cdot D_j^{(i)}} \cdot \frac{\sum_{j=t-T}^{t-1} w_j \cdot P_j}{P_t - \sum_{j=t-T}^{t-1} w_j \cdot P_j} \quad (\text{D.4})$$

This resulting formulation of the final demand still incorporates the growth and seasonal rates, while implementing an averaging approach; the resulting expression of simulated demand is:

$$D_t^{(i)} = \tilde{D}_t^{(i)} \cdot \left(1 + r^{(i)} + s_t^{(i)}\right)^{0.25 \cdot \sum_{j=t-T}^{t-1} x_j \cdot (t-j)} \quad (\text{D.5})$$

where we substitute $\tilde{D}_t^{(i)}$ with its expression obtained from (D.4).

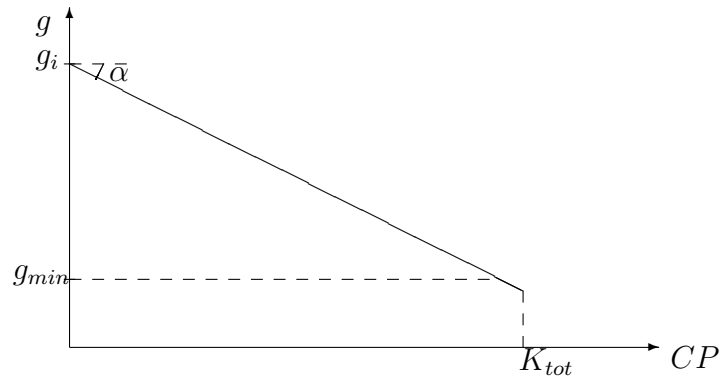
Appendix E

Mine Expansion Theory

This appendix outlines the simulation framework developed to treat mine expansion and related mine dynamics, implemented in the model.

Ore grade degradation

Ore grade can be expected to degrade over time as a given mine extracts more and more material. Hence, one can expect that there will be a relationship between ore grade g and cumulative production CP . As a working approximation, the model assumes that this relationship is linear, and downward-sloping. The following graph presents this relationship:



K_{tot} is the expected total output of the mine, as assessed by the investor when opening the site. Both K_{tot} and g_{min} (the limiting ore grade, below which production is not economically feasible—essentially the limit between resource and reserve) are model inputs, and represent *feasibility limits*. α is the absolute value of the slope and

is given for each mine; similarly, g_i is the grade of the ore extracted when the mine opens.

With this framework, mines of differing grades and operating lifetimes can be simulated. Some working rules of thumb can be readily modeled using these inputs. For small mines, assuming a smaller ore body, one would expect the g - CP line to decline at a relatively more rapid rate, resulting in a steeper line, limiting the opportunities for expansion. The following modeling rule has hence been adopted to determine whether or not expansion is possible:

$$\begin{cases} \alpha > \bar{\alpha} & : \text{no expansion} \\ \alpha \leq \bar{\alpha} & : \text{expansion} \end{cases}$$

with α the *absolute value* of the slope, representing the percent ore grade reduction per unit of ore extracted.

The relationship between ore grade and cumulative production can be formulated as follows:

$$g(t) = \begin{cases} g_i - \alpha \cdot CP & \text{if } g > g_{min} \text{ and } CP(t) \leq K_{tot} \\ 0 & \text{otherwise} \end{cases}$$

Relationship between the average cost and quantity produced

Let $Q(t)$ be the quantity of the element that is mined at t , $R(t)$ the quantity of matter extracted at t . This provides:

$$\forall t, Q(t) = g(t) \cdot R(t)$$

Let AC be the unit average cost of production. As a first approximation, AC can be defined using the following expression:

$$AC(t) \cdot Q(t) = R(t) \cdot VC + \frac{\text{capital}}{\tau_{\text{life}}}$$

with VC the variable cost of extraction, and $\chi = \frac{\text{capital}}{\tau_{\text{life}}}$ the capital invested initially, discounted for the expected lifetime of the mine (again, from the investor's point of view). This expression becomes:

$$AC(t) = \frac{VC}{g(t)} + \frac{\chi}{Q(t)} \quad (\text{E.1})$$

If the variable cost of extraction is relatively constant over time and given an initial rated production and minimum average cost, the variable cost can be calculated by using Equation E.1 (where A_i^* is the initial minimum average cost $AC_i(t_0)$, and Q_i^* is the corresponding initial optimal production $Q_i(t_0)$):

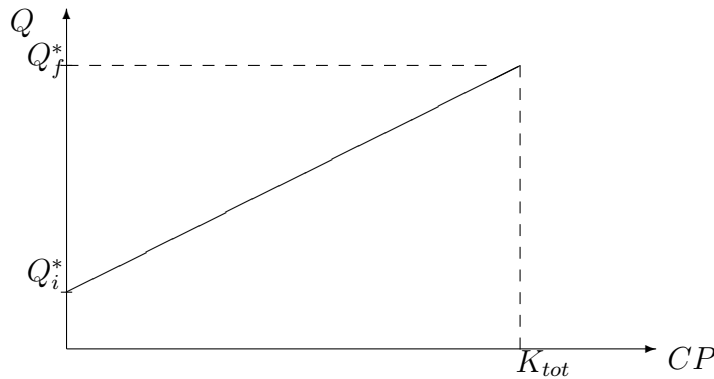
$$A_i^* = \frac{VC}{g_i} + \frac{\chi}{Q_i^*}$$

$$\text{i.e. } VC = g_i \cdot \left(A_i^* - \frac{\chi}{Q_i^*} \right)$$

There is now an explicit (and computable) relationship between $AC(t)$ and $Q(t)$, and more specifically for our model, between A^* and Q^* .

Expression for the optimal production Q^*

Again, the model assumes a linear relationship — that can be either upward-, downward-sloping, or constant — between Q^* and the cumulative production CP . Instead of being defined by its slope, it will this time be defined by two points: initial, and at K_{tot} (as envisioned by the investor).



Hence

$$Q(t) = Q_i^* + \frac{Q_f^* - Q_i^*}{K_{tot}} \cdot CP(t)$$

Now Q_f^* should be calculated. From the assumption that the investor envisions a production at $Q^*(t)$ at each period, Q can be replaced by Q^* . Moreover, $CP(t) = \int_{t_i}^t Q(t)dt$.

Deriving the expression for $Q(t)$ once with respect to t , we obtain a first-order linear differential equation:

$$\frac{\partial Q^*}{\partial t} = \frac{Q_f^* - Q_i^*}{K_{tot}} \cdot Q^*(t)$$

The solution is hence:

$$Q^*(t) = Q_i^* \cdot \exp\left(\frac{Q_f^* - Q_i^*}{K_{tot}} \cdot t\right)$$

Finally, at $t = \tau_{life}$, we have $Q^*(\tau_{life}) = Q_f^*$. The following equation provides a means to calculate Q_f^* :

$$\frac{\ln Q_f^* - \ln Q_i^*}{Q_f^* - Q_i^*} = \frac{\tau_{life}}{K_{tot}}$$

Using the function *Goal Seek* in Excel[®], Q_f^* can be estimated numerically within the model.

Derivation of the minimum average cost A^*

Given the expression (E.1), $A^*(t)$ can be derived from the calculation of $Q^*(t)$ by simply applying this formula to the point where the average cost is minimal, and we hence obtain:

$$A^*(t) = \frac{VC}{g(t)} + \frac{\chi}{Q^*(t)}$$

This mine dynamics approach is implemented in the model and is used to account for mine expansion when running simulations over several years.

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